

REF-ET: REFERENCE EVAPOTRANSPIRATION CALCULATION SOFTWARE
for FAO and ASCE Standardized Equations

Version 2.0 for Windows
for Windows 95, 98 and NT



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REF-ET

Reference Evapotranspiration Calculator

Version - Windows 2.0

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The REF-ET program provides standardized calculations of reference evapotranspiration¹ (ET) by fifteen of the more common methods currently in use. The two primary purposes of REF-ET are to:

- 1) **Provide standardized reference ET calculations that can be compared with other ET computer programs for various weather data sets (i.e., data files).**
- 2) **Provide standardized reference ET calculations using data from a wide range of data file types, data unit types and timesteps.**

The REF-ET program supports reference ET computation guidelines and procedures that were recommended in ASCE Manuals and Reports on Engineering Practice No. 70, "Evapotranspiration and Irrigation Water Requirements" edited by Jensen, et al., (1990) through efforts by the Committee on Evapotranspiration in Irrigation and Hydrology of the Irrigation and Drainage Council of the Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE). REF-ET provides calculations that are compatible with United Nations Food and Agriculture Organization (FAO) Irrigation Paper No. 56 (Allen et al., 1998) and with standardized forms of the ASCE Penman-Monteith equation recommended in 2000 by the ASCE Task Committee on Standardized Evapotranspiration Calculations.

¹ Reference evapotranspiration is defined as the ET from an extensive surface of clipped grass or alfalfa that is well-watered, and fully shades the ground. The clipped grass reference is considered to be a "cool-season" grass variety such as perennial fescue or ryegrass. The FAO-24 publication by Doorenbos and Pruitt (1977) suggested that the clipped grass surface be maintained at 8 to 15 cm in height. FAO-56 has suggested that the reference definition for clipped grass be fixed at 12 cm height for computational and definition purposes. The FAO-56 Penman-Monteith equation has been recommended by FAO to represent the definition of the grass reference (albedo = 0.23, height = 0.12 m, surface resistance = 70 s/m). The alfalfa reference is generally considered to occur from alfalfa that is greater than 0.30 m in height and that has full ground cover. The ASCE Manual 70 (Jensen et al., 1990) has suggested fixing the height of the alfalfa reference at 0.5 m for computational and definition purposes.

Reference ET Methods Calculated by REF-ET for Windows Version 2

Table 1. Reference ET methods calculated by REF-ET.

Method	Timesteps	Ref. Type
a) "full" ASCE Penman-Monteith with resistances by Allen et al, 1989	(M, D, or H)*	ET _O ET _r
b) "full" ASCE Penman-Monteith with user supplied surf. resistance	(M, D, or H)*	ET _O ET _r
c) Standardized form of the ASCE Penman-Monteith by ASCE 2000	(M, D, or H)*	ET _O ET _r
d) 1982 Kimberly Penman (Wright, 1982; 1987; 1996)	(M, D, or H)*	ET _O ET _r
e) FAO 56 Penman-Monteith (1998) with resistance for 0.12 m grass	(M, D, or H)*	ET _O
f) 1972 Kimberly Penman (fixed wind func.) (Wright & Jensen 1972)	(M, D, or H)*	ET _r
g) 1948 or 1963 Penman (Penman, 1948; 1963)	(M, D, or H)	ET _O
h) FAO-24 Corrected Penman (Doorenbos and Pruitt, 1975, 1977)	(M or D)	ET _O
i) FAO-PPP-17 Penman (Freres and Popov, 1979)	(M or D)	ET _O
j) CIMIS Penman (hourly only) with FAO-56 R _n and G=0	(H)	ET _O
k) FAO-24 Radiation Method (Doorenbos and Pruitt, 1975, 1977)	(M or D)	ET _O
l) FAO-24 Blaney-Criddle (Doorenbos and Pruitt, 1975, 1977)	(M or D)	ET _O
m) FAO-24 Pan Evaporation Method (Doorenbos and Pruitt, 1977)	(M or D)	ET _O
n) 1985 Hargreaves Temperature Method (Hargreaves and Samani)	(M or D)	ET _O
o) Priestley-Taylor (1972) Radiation and Temperature Method	(M or D)*	ET _O
p) Makkink (1957) Radiation and Temperature Method	(M or D)*	ET _O
q) Turc (1961) Radiation and Temperature Method	(M or D)*	ET _O

*M = Monthly calculation time step; D = Daily (24-hour) calculation time step; H = Hourly or shorter time step. Equations h, l, and k-q are limited to monthly or daily calculation time steps due to the nature or form of the equations or parameters required. ET_O refers to grass reference ET (e.g., "short" reference) and ET_r refers to alfalfa reference ET (e.g., "tall" reference). The specific methods used to predict net radiation, soil heat flux, resistances, etc. for each method are described in a later section of this manual.

The REF-ET program is designed to read weather data from any ASCII (regular text) data file. REF-ET can also read measured ET data from the same file, for example ET data measured from a lysimeter. The latter data are useful for comparing with calculated ET. REF-ET can be conveniently instructed to read any type of text data format, including unformatted data from an ASCII file where data are separated by spaces, commas or tabs.

The format of the weather data file is defined using a file "definition" procedure that is built into the REF-ET program. This file definition procedure creates a "definition file" that contains information that describes the data format and order of data within the specific data file and the types of measurement units. The definition file also contains supplementary weather site information including the heights of anemometer and temperature sensors, weather station elevation, the location latitude and longitude, default day/night wind ratio, etc. The definition file of of REF-ET for Windows version 2.0 also includes the selection of the specific reference ET equations and reference type that the user desires to calculate.

Computation Time Steps

REF-ET can compute reference ET on monthly, daily, or hourly (or shorter) time steps. Monthly and daily computations are presented as mm/day or inches/day and computations for time steps that are shorter than 24-hours are presented as mm/hour or inches/hour.

Hourly computations (or computations for other periods shorter than 24-hours) are presented for the Penman-Monteith, 1982 Kimberly Penman, CIMIS, and 1963 Penman equations only. REF-ET automatically determines the proper time step to use for computations from the data file. The day of the year or Month and Day of Month must be read for each line of the data file (even for hourly data), as this information is needed to compute extraterrestrial radiation, net radiation, and wind function parameters in the Kimberly Penman equation.

REF-ET Installation and Computer System Requirements

REF-ET for Windows is written in Visual Basic Version 6.0, Professional Edition. REF-ET runs on computers that have Windows 95, 98, or Windows NT operating systems. The screen resolution must be set to 800 x 600 or higher². Screen resolutions of 640 x 480 will not show the entire REF-ET data screens.

The two REF-ET distribution diskettes or the REF-ETzp.exe file that is downloadable from the www.kimberly.uidaho.edu web site contain the REF-ETw.EXE program file and assorted data and example files along with required Microsoft Visual Basic system files. The distribution diskettes and the downloadable REF-ETzp.exe file contain a file named "Setup.exe" that is used to install REF-ET program onto the computer.

If the "self-extracting" REF-ETzp.exe file is utilized, it will first need to be "unzipped" in order to place the setup files onto the computer. This is done by double clicking on it in the Windows Explorer window or using some other File Manager. The REF-ETzp.exe file only needs to be "run" once to unzip it. The product will be the creation of the following six files in the folder that the user specifies.

The REF-ETzp.exe file (or two distribution diskettes) contains the following files:

SETUP.EXE
SETUP.LST
REF-ET1.CAB
REF-ET2.CAB
Examples.exe
Readme.txt

The REF-ET1.CAB and REF-ET2.CAB are Microsoft "Cabinet" files that contain the REF-ETw.exe and Visual Basic system files. The Setup.LST file contains instructions for SETUP.EXE to process when it is run during installation.

The Examples.exe file is a "self-extracting" zipped file that contains various example data sets and associated definition files that are described later. This file can be unzipped into the REF-ET folder or other folder after it has been created during installation of REF-ET.

² Some computer screens that are running in 800 x 600 mode may need to have the "small fonts" option selected in the Windows operating system in order for all REF-ET screens to display fully. This is done by selecting (from the Windows screen): Start – Settings – Control Panel. In the Control Panel window double click on the Display icon. Select the Settings menu tab. Then select the Advanced button. On the Advanced window, under the General menu tab, select "Small Fonts" from the Fonts item. Press OK twice.

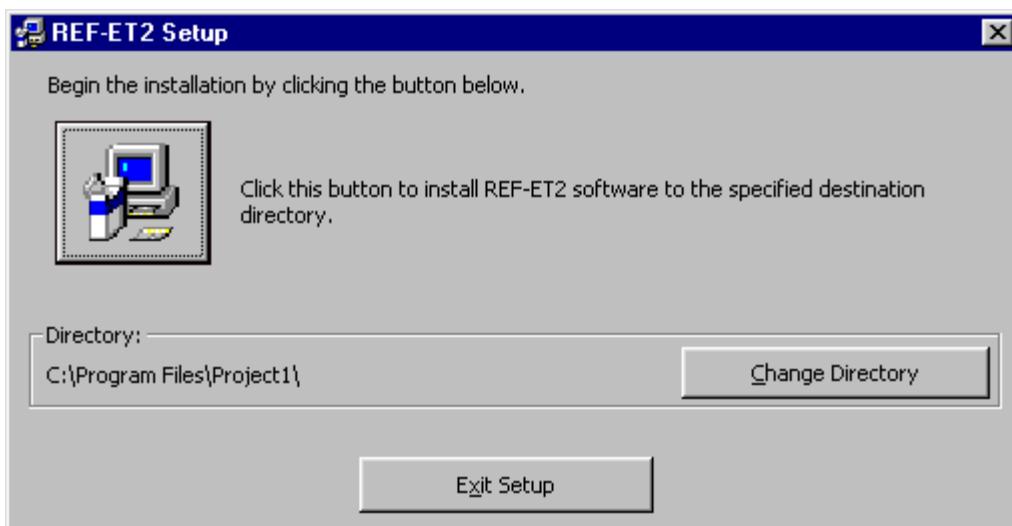
Examples.exe is unzipped by double clicking on it in the Windows Explorer or other File Manager Software.

REF-ET can be installed directly from the distribution diskettes or the files can be copied into a temporary folder (directory) on the hard drive. If the self-extracting REF-ETzp.exe file is used, then this file can be unzipped into a temporary folder as well (by running it once).

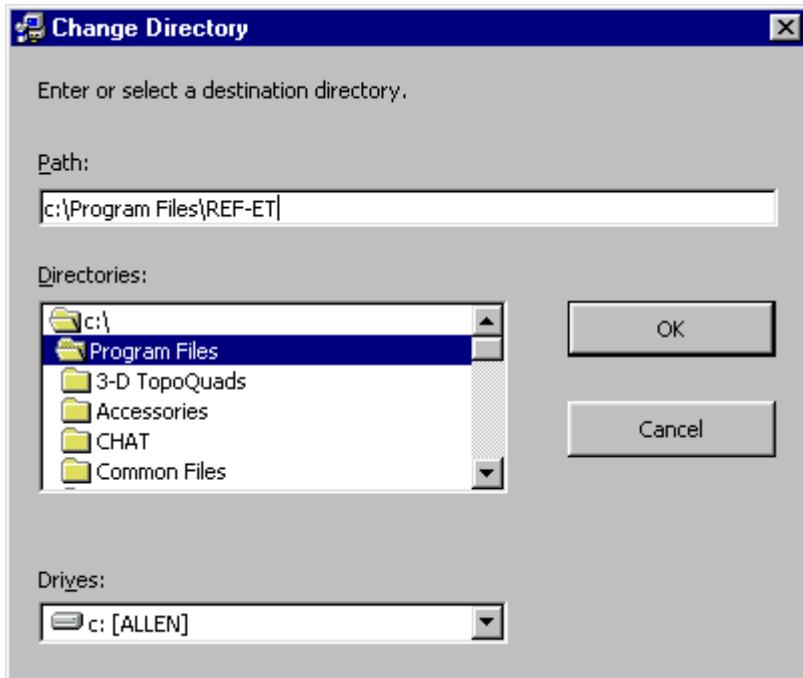
If installing from the diskette, insert diskette 1 into the floppy drive and Press the Windows "Start" button. Then select "Run..." from the menu and type in A:Setup or B:Setup depending on the drive letter associated with the floppy disk drive.

If installing from a temporary folder on the hard drive, enter this folder via the Windows Explorer or other file manager and double click on the file named Setup.exe.

After the Setup.exe has started, it will initially display the message "Copying files. Please stand by." During this time, Windows is copying files from the CAB files into a temporary location. Setup will then advise the user to exit all other programs to reduce the chance of a shared file violation. At this point, the user can select the cancel button to cancel the installation. If the user wishes to proceed, he/she should press the "OK" button on the screen. The following screen is then presented.



The Setup screen shown above lists a recommended Directory (folder) into which to place the REF-ETw.exe file. The folder will typically be a folder within the "Program Files" folder. However, the user can place Ref-ET wherever he/she wishes. To change the folder, select the "Change Directory" so that the following window is presented:



The “Change Directory” window is where the user can select an existing folder into which REF-ETw.exe will be installed, or the user can type in a new folder name in the slot titled “Path:”. For example, in the above window, the user has selected the “Program Files” folder in the Directories window and then has typed in “REF-ET” in the Path window so that a new sub-folder named REF-ET will be created. Press OK when ready. If the indicated “path” does not exist, then Windows will present a confirmation window asking the user to confirm the creation of the new folder. The user will then be brought back to the first window presented above.

The user should click on the “icon” shown in the first window above that shows a picture of a computer.

The user will then be presented a window asking for confirmation to create a “program group.” Select “Continue.”

The Setup program will then copy the REF-ETw.exe and other Visual Basic “DLL” and “OCX” files to the hard drive. Some of these files will be written to the Windows/System folder. When the file transfer has been accomplished, Windows will indicate that the installation has been successfully completed.

After installation, the “CAB” files can be deleted from the hard drive.

You can now run REF-ET by selecting the Windows “Start” button, then select “Programs” and “REF-ET” from the list.

Creating a Shortcut and Screen Icon for REF-ET

You can run REF-ET by selecting the Windows “Start” button, then select “Programs” and “REF-ET” from the list. However, for convenience you may wish to create a shortcut for REF-ET so that an icon is present on the computer screen at all times. A shortcut is created by entering into the Windows Explorer or other file manager program and going to the folder that contains REF-ETw.exe. This will be the folder indicated during installation. When the REF-ETw.exe file is found, right-click on the name REF-ETw.exe (using the right mouse button) and select the option “Create Shortcut...”. In Windows Explorer, this will create a “shortcut” file having the same name as REF-ETw. After this new file is created, the user should drag this new file onto the Windows screen using the mouse (this is done by clicking the left button of the mouse on the file name and while holding the left button down, dragging the file name off from the Explorer window).

The result of creating the new shortcut and dragging it to the Windows screen will be a small icon that has an “ET” on it and that has “short cut to REF-ETw” below it (). REF-ET can be operated by double clicking on this shortcut icon.

Disclaimer

NOTE: Neither the American Society of Civil Engineers, the United Nations Food and Agriculture Organization, the University of Idaho, nor the author of REF-ET (R.G. Allen) accept any liability for errors or incorrect results from the REF-ET program nor any problems associated with installation of the software onto the user’s computer system.

The REF-ET program includes commonly used algorithms and assumptions required in estimating reference ET. However, application of the REF-ET program to various combinations or types of data may occasionally violate assumptions or may require extrapolation beyond endpoints of algorithms, resulting in incorrect ET and parameter estimates. Therefore the user of this software assumes all responsibility and reliability for accuracy and correctness of estimates.

Distribution and Support Limitations

All source code and executable code of the REF-ET program is copyrighted by the author, Dr. Richard G. Allen and the University of Idaho, 1999, 2000. Users are given permission by the author to distribute the executable code contained on the distribution disks or in the downloadable REF-ET.zip file provided that the University of Idaho logo and author titles are retained, and with the understanding that users of distributed copies will subsequently register their copies of REF-ET with the University of Idaho upon use of their copy. An invoice for payment of the registration can be obtained from <http://www.kimberly.uidaho.edu/REF-ET/> or by making a request to REFETinv@kimberly.uidaho.edu.

When REF-ET is distributed to students of Universities, a \$10.00 license fee must be sent to the University of Idaho for each copy of REF-ET distributed. Students are expected to register the software with the University of Idaho upon graduation from their university and if subsequent use of the software is for commercial or professional purposes. **No**

permission is granted to distribute any modifications of either the executable nor source code of the REF-ET program without prior, written consent by the author. In addition, No permission is granted to distribute the REF-ET program commercially.

The University of Idaho will provide limited telephone and written support to registered users of REF-ET who have purchased copies of the program directly from the University of Idaho. No telephone nor written support is available to nonregistered users or to users who have obtained or purchased copies from sources other than the University of Idaho.

The REF-ET Windows Version requires Windows 95 or 98 or NT and at least 800 x 600 screen resolution to run. The software is available from The University of Idaho, at the following address, in executable form on 3.5 inch (1.44 MB) floppy diskettes.

Users may purchase a copy of REF-ET or may register their copy of REF-ET with the University of Idaho by enclosing a check or money order for \$49.00 plus \$4.00 shipping and handling (\$15.00 shipping and handling addresses outside of the North American continent) addressed to:

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Kimberly, Idaho 83341, U.S.A.

Telephone: 1 (208) 423-4691
Fax: 1 (208) 423-6559
mail: REFETinv@kimberly.uidaho.edu

Example Data Files

Example data files have been included on the REF-ET distribution diskette or in the downloadable REF-ET.zip file. These files are contained in the zip file named Examples.zip. These data files are useful for verifying correct execution of the REF-ET program and to serve as examples of program execution and results. Example files include:

- | | |
|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ASCE.DAT | The average monthly data set used in Chapter 6 of the ASCE Manual 70 "Evapotranspiration and Irrigation Water Requirements" by Jensen et al., (1990). This file provides calculations of average monthly alfalfa reference ET that are similar to those presented in Chapter 6 of the ASCE manual 70 for the month of July at Kimberly, Idaho. |
| KIMB6971.DAT | Average monthly data set for Kimberly, Idaho used in the analysis in Chapter 7 of ASCE Manual 70 (Courtesy of J.L. Wright). Average of years 1969-71. |
| KIMWSA85.DAT | Daily weather data from the National Weather Service station at Kimberly, Idaho |

LOGAN90H.DAT 30-minute weather and lysimeter data for August 16-19, 1990 at Logan, Utah in Campbell Scientific Inc. data logger format.

FAO56x17.dat The montly ET_o calculation example 17 from FAO-56 (1998)

FAO56x18.dat The daily ET_o calculation example 18 from FAO-56 (1998)

FAO56x19.dat The monthly ET_o calculation example 19 from FAO-56 (1998)

The example data files have associated "definition" files that are titled ASCEEX.DEF, ASCEw.DEF, KIMB6971.DEF, KIMWSA85.DEF, LOGAN90H.DEF, FAO56x17.DEF, FAO56x18.DEF and FAO56x19.DEF. These definition files (.DEF) were created by REF-ET and are read and used by the REF-ET program to indicate the format and measurement units of weather data contained in the associated data files.

Algorithms Used in the REF-ET Program

The basic algorithms and routines used in REF-ET are taken from ASCE Manuals and Reports on Engineering Practices No. 70, "Evapotranspiration and Irrigation Water Requirements" (Jensen, et al., 1990), from Allen et al., (1994b), from FAO-56 (Allen et al., 1998), and from the report on Standardization of Reference Evapotranspiration Calculations drafted by the ASCE Committee on Evapotranspiration in Irrigation and Hydrology during the year 2000.

Some of the algorithms may deviate slightly from those applied in Chapter 6 or listed in Chapter 7 of the ASCE Manual 70. Appendix A of this users manual lists the specific equation forms for the Penman and Penman-Monteith equations and for the supporting intermediate parameters. Specific items to note for REF-ET are:

- 1) Unless the height of vegetation is specified in the data file for each line of data, the value of d, zero-plane displacement, used in the ASCE Penman-Monteith method is estimated as 0.67 times the height of the weather measurement surface in REF-ET (Eq. 6.22 in Manual 70) in order to help account for the effect of the height of the measurement vegetation on the resulting wind profile (see equation 2 in Appendix 1 and Equation 2-27 in Appendix 2). The example in Chapter 6 of Manual 70 used 0.667 times the height of the reference crop (alfalfa). In REF-ET, if the height of vegetation for the weather measurement site is not entered (i.e., it is set to zero), then d will be calculated as 0.67 times the height of the reference crop (grass or alfalfa) being calculated.
- 2) The correction factor c for the FAO-24 Penman and the a and b coefficients for the FAO-24 Blaney-Criddle and Radiation methods and the K_p factor for the FAO-24 pan method are computed using regression equations developed by Allen and Pruitt (1991). These regressions are presented in Appendix E of Manual 70 and are different from those by Frevert et al (1983) used in the examples of Chapter 6 of manual 70. REF-ET places limits on values of regression parameters equal to those set by FAO 24 (see Allen and Pruitt (1991) or Appendix E, Manual 70).

Reference ET Options

REF-ET provides the option of computing either grass or alfalfa ET reference estimates. For the ASCE Penman-Monteith equation, different algorithms are used for leaf area index (LAI) and bulk stomatal resistances (Allen et al, 1989, Jensen et al., 1990), depending on the type of ET reference (see Eq. 5 and 6 in Appendix 1). If the height of the crop or reference vegetation (for example, as occurring in a lysimeter) is read for each hour, day or month from the data file, then these heights will override the standard reference height that is specified in the definition file.

For all “grass reference” equations other than the ASCE Penman-Monteith equation, alfalfa reference ET_r is calculated by multiplying by a user specified reference ratio ET_r/ET_o . Grass reference ET_o is calculated for all “alfalfa reference” equations (other than the ASCE Penman-Monteith and the Kimberly Penman equations) by dividing by the user specified reference ratio ET_r/ET_o . In the case of the Kimberly Penman equation, a special grass wind function is used for predicting grass ET_o (Wright, 1996) and a special alfalfa wind function is used for predicting alfalfa ET_r . In the case of the ASCE Penman-Monteith equation, specific resistance parameters are used for each reference type.

Usually an alfalfa to grass reference ratio of 1.25 should be used for arid or semiarid climates and a ratio of about 1.10 to 1.15 should be used for humid climates. However, the reference ratio may range from 1.10 to 1.35, depending on the grass type, height, and climate. An equation for predicting a reference ratio as a function of climate is given in Appendix 4-1 of Appendix 4. A value of 1.15 was used in Chapter 6 of Manual 70 (Jensen et al., 1990).

Equation Requirements

Specific algorithms used with the various Penman equations are listed in Table 2 later in this users manual. The equation reference numbers refer to equations presented in Appendices 1 – 4 of this manual.

The FAO-56 Penman-Monteith method and associated intermediate parameters are computed as presented in FAO-56. The method for computing R_n for the FAO-56 PM, referred to as R_n FAO-56 uses equations 24, 25, 26 and albedo = 0.23 as indicated in Table 2.

Actual Vapor Pressure of the Air

Actual vapor pressure of the air, e_a , is computed in a number of ways, as indicated in Eq. 17 – 22 of Appendix 1. Ordinarily, only one type of vapor pressure information (i.e., either dewpoint temperature, relative humidity, vapor pressure, or wet bulb/dry bulb temperature) should be read into REF-ET. This is done by limiting the specific columns of data that are read by REF-ET from the data file. Unnecessary or unwanted data columns can be skipped over by the REF-ET program, as explained in a later section that describes the creation of the definition file.

When two or more types of humidity information are read into REF-ET, then the program must decide which particular information to use in computing e_a . For example, if both

dewpoint temperature and relative humidity are read in, REF-ET must decide on which parameter to use in a Penman or Penman-Monteith equation. Therefore, a priority system has been built into REF-ET that computes e_a in order of priority, unless a higher priority component is missing for that day or hour. The priority order is listed near the end of Table 2.

Parameter Equations Used in Various Penman Equations

Table 2 lists the various parameter equation numbers used in the Penman Equations. These numbers refer to equations listed in the middle section of this manual and in the appendices.

Variations on the ASCE Penman-Monteith Equation in REF-ET

There are four entries in REF-ETw for the Penman-Monteith equation as shown in Table 1. The first two entries shown in Table 1 are both for the full ASCE-PM equation. The first entry utilizes the standard aerodynamic resistance, Leaf area index and surface resistance relationships for grass and alfalfa reference crops that were reported by Allen et al., (1989) and listed in ASCE Manual 70. The second entry uses the same aerodynamic relationships as the first entry, but it uses values of surface resistance that are entered by the user. This is explained in detail later.

The FAO-56 PM equation is a simplified form of the ASCE PM equation that is applied to a 0.12 m tall grass reference crop and has simplifications regarding latent heat of vaporization, air density, and aerodynamic resistance. In the same manner, the ASCE "standarized" forms of the ASCE Penman-Monteith equation utilize these same types of simplications and are applied to both grass and alfalfa references. The standarized ASCE Penman-Monteith equation for grass is identical to the FAO-56 PM equation.

Table 2. Parameter equation numbers, etc. used in the various Penman Equations.

	ASCE Full Penman-Monteith	ASCE Std. Penman-Mont.	FAO-56 Penman-Monteith	1963 Penman	FAO-24 Corrected Penman	1982, 1996 Kimberly Penmans	CIMIS Penman w/FAO56 R _n
Δ	14	14	14	14	14	14	14
γ	13	FAO-56-13	FAO-56-13	13	13	13	13
λ	7	$\lambda = 2.45 \text{ MJ/kg}$	$\lambda = 2.45 \text{ MJ/kg}$	7	7	7	7
P	9b	9b	9b	9b	9b	9b	9b
α	$\alpha=0.23$	$\alpha=0.23$	$\alpha=0.23$	$\alpha=0.23$	$\alpha=0.25$	46	$\alpha=0.23$
R _n	24, 25, 26	24, 25, 26	24, 25, 26	24, 25, 26	24, 25, 42, T _{mean} 4	24, 25, 42-45	24, 25, 26
G	28, 30, 32, 33	28, 30, 32, 33	28, 30, 32, 33	28, 30, 32, 33	28, 30, 32, 33	46, 30, 32, 33	G=0
R _{so}	35 day, 2.6-2.9 night	35 day, 2.6-2.9 night	35 day, 2.6-2.9 night	35 day, 2.6-2.9 night	35 day, 2.6-2.9 night	35 day, 2.6-2.9 night	35 day, 2.6-2.9 night
u ₂	Uses u _z	2-27	2-27	2-27	2-27	2-27	2-27
r _s	3	Eq. 3, 5 are embedded in Eq. 36, Table A-1	Eq. 3, 5 are embedded in Eq. 37, 38	n/a	n/a	n/a	n/a
r _a	2	Eq. 2 is embedded in Eq. 36, Table A-1 for h=0.12m, h=0.5 m	Eq. 2 is embedded in Eq. 37, 38 for h=0.12m	n/a	n/a	n/a	n/a
LAI	5, 6	Eq. 5 is embedded in Eq. 36, Table A-1 for h=0.12m, h=0.5m	Eq. 5 is embedded in Eq. 37, 38 for h=0.12m	n/a	n/a	n/a	n/a
ρ	11	embedded in Eq. 36, Table A-1	embedded in Eq. 37, 38	n/a	n/a	n/a	n/a
T _{kv}	12	embedded in Eq. 36, Table A-1	embedded in Eq. 37, 38	n/a	n/a	n/a	n/a
e _s	16	16	16	e ^o (T _{mean})	e ^o (T _{mean})	16	16
ea	order of preference is 17, 18, 20, 21, 22						
ET _o or ET _r	1	36, Table A-1	37, 38	39	39	39-41	39

Numbers in cells refer to equations listed in Appendix 1.

The variations on the ASCE Penman-Monteith equation are described as follows:

- (1) **"full" ASCE Penman-Monteith using resistance equations by Allen et al, (1989)** is the standard, "classical" "ASCE PM" equation that uses resistance terms as described in Allen et al., (1989) and in ASCE Manual 70. In this equation, r_s is computed from leaf area index (LAI), which in turn is computed from the height specified for the reference type (grass or alfalfa). Different algorithms for LAI are used depending on reference type. The value of r_s (and r_a) will change in this standard ASCE method with height specified for the reference. The values for r_s for 24-hour timesteps, based on the ASCE LAI algorithms, are $r_s = 70 \text{ s m}^{-1}$ for 0.12 m tall grass and $r_s = 45 \text{ s m}^{-1}$ for 0.5 m tall alfalfa. The values for r_s for hourly or shorter timesteps are $r_s = 50 \text{ s m}^{-1}$ for 0.12 m tall grass and $r_s = 30 \text{ s m}^{-1}$ for 0.5 m tall alfalfa during daytime hours and $r_s = 200 \text{ s m}^{-1}$ for both 0.12 m tall grass and 0.5 m tall alfalfa during nighttime hours. These values are varied according to the value for LAI when vegetation heights are specified differently than 0.12 and 0.5 m.
- (2) **"full" ASCE Penman-Monteith with user supplied resistance** is the same as number 1, except that different values for 24-hour, daytime and nighttime surface resistance, r_s , can be specified by the user on one of the "definition" menus (Fig. 5). These specific values are then varied within REF-ET if the reference vegetation height, if read from the data file during each time step, varies from the height specified on the definition menu shown in Fig. 5 (see Kim6971.dat example).
- (3) **Standardized form of the ASCE Penman-Monteith equation by ASCE (2000)** is the standardized form of the ASCE PM equation specified by the ASCE Technical Committee on Evapotranspiration in Irrigation and Hydrology during 1999 and 2000. This equation has a form identical to that of the FAO-56 Penman-Monteith equation, but is applied to both alfalfa and grass reference types. For alfalfa, a height of 0.5 m is used in the ASCE resistance algorithms and for grass, a height of 0.12 m is used in the resistance algorithms. The height of the reference is fixed in the standardized form of the ASCE PM equations and can not be varied. For grass ET_o , r_s is fixed at 70, 50, and 200 s m^{-1} for 24-hour, hourly daytime, and hourly nighttime periods. For alfalfa ET_r , r_s is fixed at 45, 30, and 200 s m^{-1} for 24-hour, hourly daytime, and hourly nighttime periods. Net radiation, R_n is computed using the FAO-56 procedure and a fixed value for latent heat of vaporization, $\lambda = 2.45 \text{ MJ/kg}$. The values for r_s do not change with height of the reference within REF-ET. They are fixed.
- (4) **FAO 56 Penman-Monteith equation (1998) with 0.12 m grass resistances.** The FAO-56 PM method uses the FAO-56 R_n and a fixed value for latent heat of vaporization, $\lambda = 2.45 \text{ MJ/kg}$. The equation has incorporated a fixed height for a clipped grass equal to 0.12 m that implies a specific roughness height and a surface resistance of 70 s m^{-1} . When the wind, temperature and humidity measurement heights are presumed to be at 2 m above a 0.12 m tall grass, the aerodynamic resistance, r_a becomes $r_a = 208/u_2$ where u_2 is wind speed in m s^{-1} . For consistency, a fixed value for $\lambda = 2.45 \text{ MJ/kg}$ is used to compute the psychrometric constant, γ . Because of the fixed height and resistances, the FAO-PM equation is limited to the prediction of grass reference ET_o . Following FAO-56, the value for r_s is fixed at 70 s m^{-1} for both 24-hour and hourly time-steps.

Intermediate Computation Files

The REF-ET program has the option of creating disk files of intermediate parameter calculations, for example computation of net long wave radiation, R_n , Δ , ρ , etc. This option is useful in checking through program calculations and for comparisons with intermediate calculation results from other ET programs. There are two intermediate files that can be created by REF-ET. The first intermediate file echoes the values of data parameters read from the original file, to allow the user to verify correct parameter format definition and to insure that the data file is being read properly. The second intermediate file lists a number of intermediate parameters calculated within REF-ET that are required for final ET computations. Examples of this file are included in the appendix. Units in the second intermediate file (this file has an extension of ".in2") can be in SI or "English" units, depending on the selection by the user.

Definition File Editor

REF-ET creates and uses a "definition" file to help describe the layout and type of weather data that are contained in the specific data file to be read by the program. REF-ET includes a built-in editor for creating the data definition file in a straightforward manner. The definition file editor allows the user to view lines of the data file in order to determine the format of the data while building the format definition file. More detailed information on the content and creation of the data definition file is included later on in this document.

Program Operation

Specific steps to operate the REF-ET program are:

1. **To operate REF-ET**, the program is launched from the Windows Explorer by double clicking on the REF-ETw.EXE file name. Or, if REF-ET has been installed using the Setup.exe procedure, REF-ET can be started by selecting the Windows "Start" button, then pressing "Programs" and selecting REF-ET from the list of installed programs. A shortcut icon can be created for REF-ET that can be placed on the Windows screen.

When REF-ET launches, it will display a title and credit screen that will then change to a second beginning screen that is shown in Fig. 1

The user can press the "About Ref-ET" button to view information on the objective of REF-ET and on how to procure an official, registered copy of the software. The user presses the button "Proceed" to begin program operation.

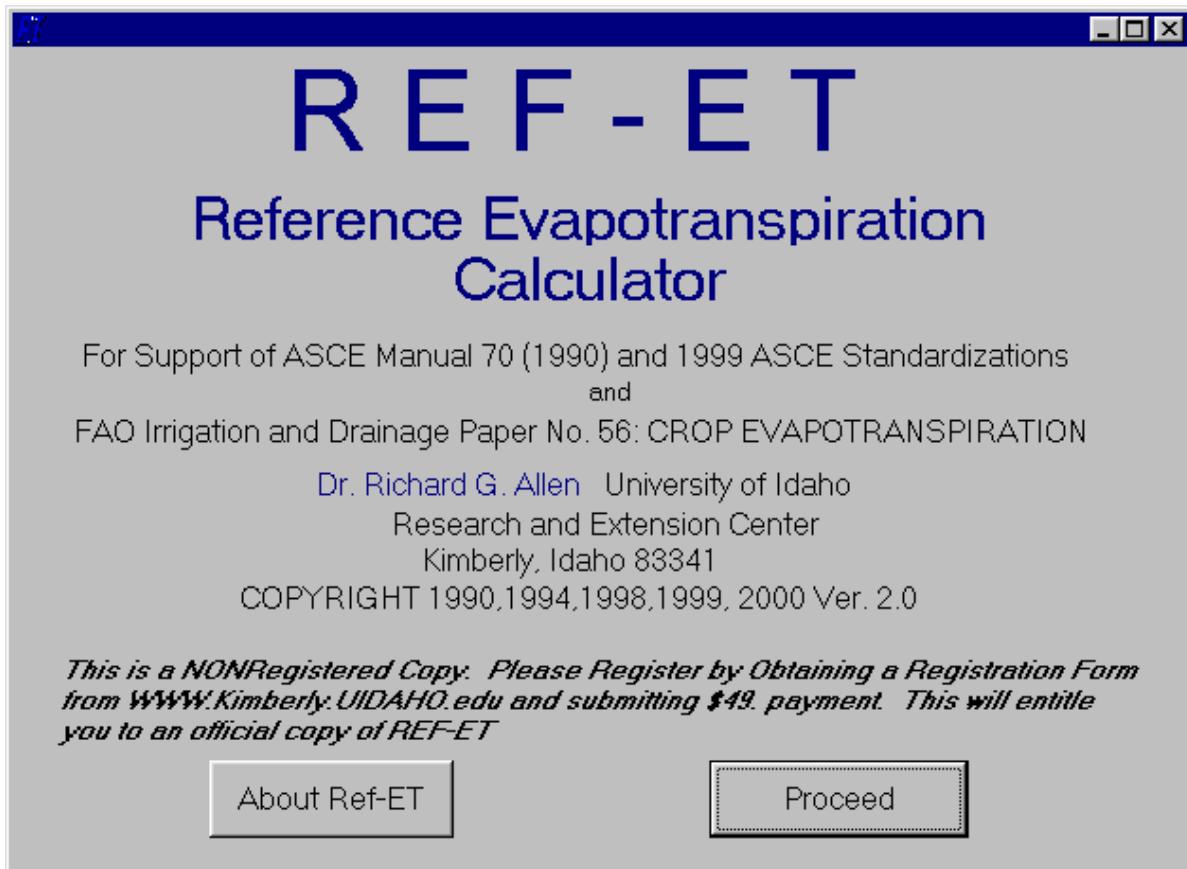


Figure 1. Introductory screen of REF-ET

Opening the data file

- When REF-ET begins operation, it displays a dialog window for opening the data file, as shown in Fig. 2. This is a standard Windows file opening dialog box. The user can change the folder in the "Look in" window to direct REF-ET to the folder that contains the weather data file. A list of all ".dat" files is displayed for the current folder. Other types of files can be displayed by changing the information listed in the "Files of type" window near the bottom of the box. The user can click on the name of a displayed file to enter the name into the "File name" window, or he/she can type the name of the file to open in the "File name" window, or the user can merely double click on the name of a file that is displayed. Pressing cancel will terminate the REF-ET program.

The data file contains weather data measurements from which reference ET will be computed. The data file can be any ASCII file. The weather data parameters do not need to be in any specific order in the file, as long as each line of data is consistent in its order. Data items in each data line can be separated by blanks (spaces), tabs, or commas. The columns of data do not need to be formatted. REF-ET will figure out when one data item ends and the next begins. When two parameters are listed in the data file side by side (i.e., with out any space between them), then REF-ET can be instructed to separate these parameters by specifying the first and last column for each

of the adjoining data items. In this case, the data file should be formatted so that the data items are in the same columns for each line of data.

One time-period of data (one time-step) can extend over multiple lines. REF-ET can be instructed to read multiple lines for each time-step by specifying when a “line-feed” occurs in the data line.

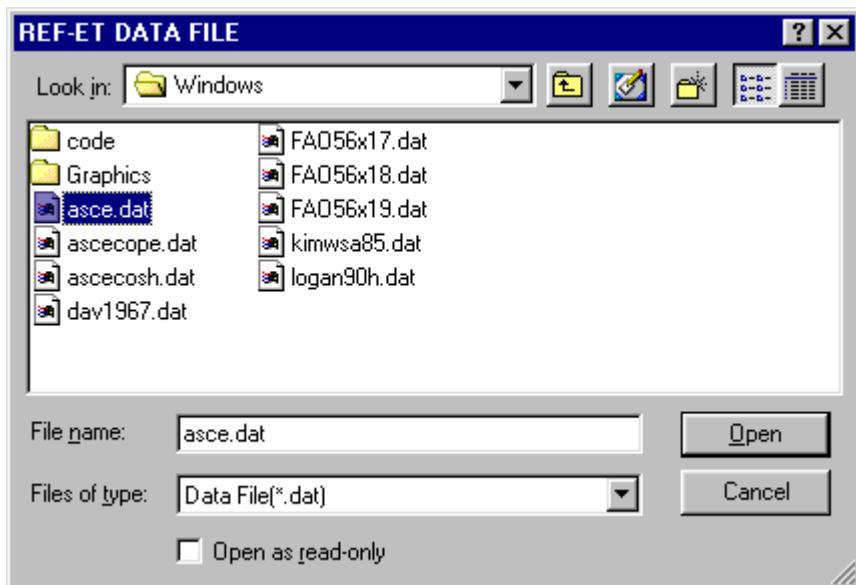


Figure 2. Dialog box for opening the definition file.

Creating an ASCII data file from a spreadsheet

If data are in a spreadsheet, an ASCII data file (.dat) can be created for the weather data by pasting the spreadsheet data into WordPad and then saving it as a text file. This is done by loading the spreadsheet file into the spreadsheet program (for example, QuattroPro or Excel), then marking the block of data columns that include all of the information that needs to be read by REF-ET (for example, date or day of year, maximum and minimum air temperature, etc.). It is OK to include column headings in the block since these can be ignored when the file is read by REF-ET. Once the block has been highlighted (marked) in the spreadsheet, select **Edit Copy** from the menu bar of the spreadsheet to temporarily copy the block into the Windows clipboard. Then, open the Windows WordPad editor (by pressing the Windows Start button and selecting Programs and then Accessories and then WordPad). Once WordPad is open, you can select **Edit Paste** from the menu bar of WordPad to paste the weather data into WordPad.

After the weather data have been pasted into WordPad, the new data file is created by selecting **File SaveAs** from the menu bar of WordPad. After selecting the folder into which to place the data, the name of the data file should be specified as -----.dat where “-----” is to be filled in by the user. In addition, the “Save as type” window should be selected so that the file type is “Text Document.” The “Text Document” file type is the same as ASCII. Then press the “Save” button.

After the “ASCII” data file has been created using WordPad, it can be read by REF-ET as a data file. All columns in the spreadsheet will be presented in the new file as “tab delimited” data. In other words, all values will be separated by tabs. Therefore, when the REF-ET definition file is created, as described in the next section, no beginning or ending column numbers need to be specified by the user, since REF-ET will recognize that the data are separated by tabs. Any “blank” columns in the spreadsheet will be represented in the WordPad data file as an extra tab. However, REF-ET will ignore this extra tab, and will go on to the next data item. Therefore, the process just described will essentially delete empty columns that were in the spreadsheet as far as REF-ET is concerned. The user will need to experiment to insure that the .dat file that is created is read properly by REF-ET. This can be done by viewing the “.IN1” intermediate file that can be created by REF-ET as described in a later section. The IN1 file contains an “echo” of the data as read in by REF-ET. This is all covered later.

The definition file of REF-ET

Now, back to REF-ET:

3. After the data file has been selected, REF-ET will present a similar dialog box for opening the **definition file**, as shown in Fig. 3 below. Again, the user can change the folder name in the “Look in” window to change the folder. A definition file is required for each data file so that REF-ET knows the order of data parameters in the data file and their units. If a definition file has never been created for the particular data file that is to be processed, then the user should type a new name for the definition file in the “File name” box and press the “Open” button. If a previously created definition file is available that describes the order, format and units of the data file, then this previously created definition file can be opened and used again. It can later be saved under a new name if desired. Definition files that were created by previous versions of REF-ET for DOS (DOS versions 2.0 or higher) can be read by REF-ET for Windows. However, additional information will need to be added by the user. In addition, when the modified definition file is saved by REF-ET for Windows, it may no longer be readable by a previous version of REF-ET for DOS. Therefore, the user may wish to use a new name when saving the edited definition file, as described later.

If the definition file has not been previously created, or if it can not be found, then REF-ET will display an error message and will ask the user to confirm that he/she wishes to create a new definition file having the name that has been specified. The user should respond “OK.” if this is the case. Otherwise, the user can correct the name specified for the definition file.

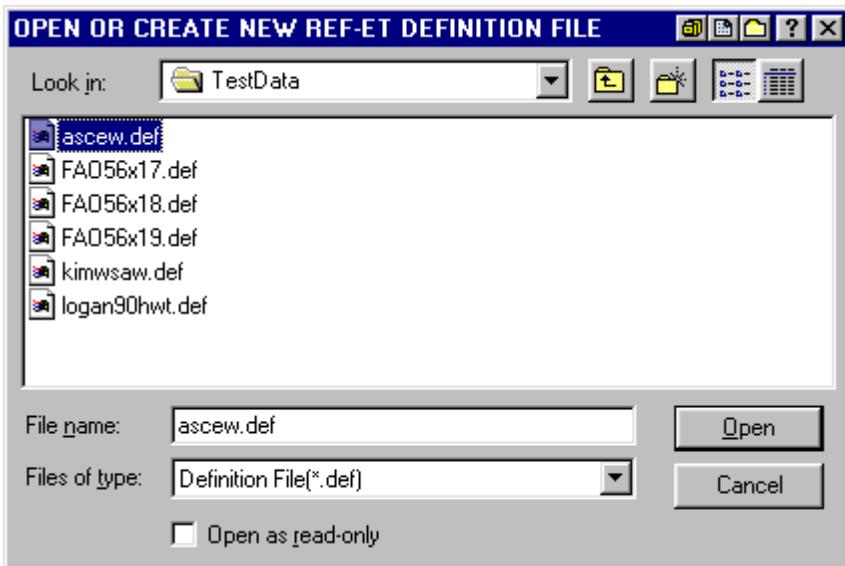


Figure 3. File open dialog box for the definition file.

4. After the definition file name has been selected or created, the user will be presented with a **definition file editor dialog box** that looks like the box presented in Fig. 4. If the definition file is being created, then the box shown in Fig. 4 will be empty of information in the upper left and lower parts. If the definition file is one that was previously created by REF-ET during a previous run, then information should appear in the “green” upper left hand corner of the editor box as shown in Fig. 4.

The upper left-hand part of Fig. 4 contains the information that describes the a) order b) location and c) units of the weather parameters that are to be read from the weather data file. For example, in the example that is in Fig. 4, REF-ET will read parameters month, day of month, maximum daily temperature in F, minimum daily temperature in F, dewpoint temperature in F, 24-hour wind speed in km/day, solar radiation in calories $\text{cm}^2 \text{ day}^{-1}$.and pan evaporation and a lysimeter (i.e., ET) measurement in mm day^{-1} . Additional parameters to be read from the file can be viewed by scrolling the scroll bars to the right of the green area.

There are four columns in the upper left-hand description area. The first column is a specific number code that describes the type of parameter and units of measurement. This number is selected by the user from the list of parameters that is in the upper right hand of Fig. 4. The parameter list has 88 parameters (see Table 3). The list can be scrolled up and down. A specific parameter can be selected by first selecting column 1 of the appropriate row in the green area of the upper left-hand description area and then finding the appropriate parameter and measurement units in the upper right hand “Parameter Identification” area and double clicking on the name of the parameter. The parameter number will be inserted into the upper left-hand description area and the full description of the parameter will be inserted into column (Fig. 4).

The bottom third of the screen shown in Fig. 4 displays the data file. This is useful when the user needs to determine starting and stopping columns for a specific data parameter. The numeric headings at the top of the data file area indicate the specific column number for each column within the data file. This viewing window can be

scrolled to the left and right and up and down, as necessary. If the parameters (columns) in the data file happen to be separated by tabs, then these tabs will show up as small vertical "bars" in the data file window. In this situation, the user should not specify beginning and ending columns for data parameters, since they are separated by tabs in the data file. REF-ET will determine how to identify and separate the data items. If a data item needs to be skipped, then the user can insert a "Dummy" variable as described later.

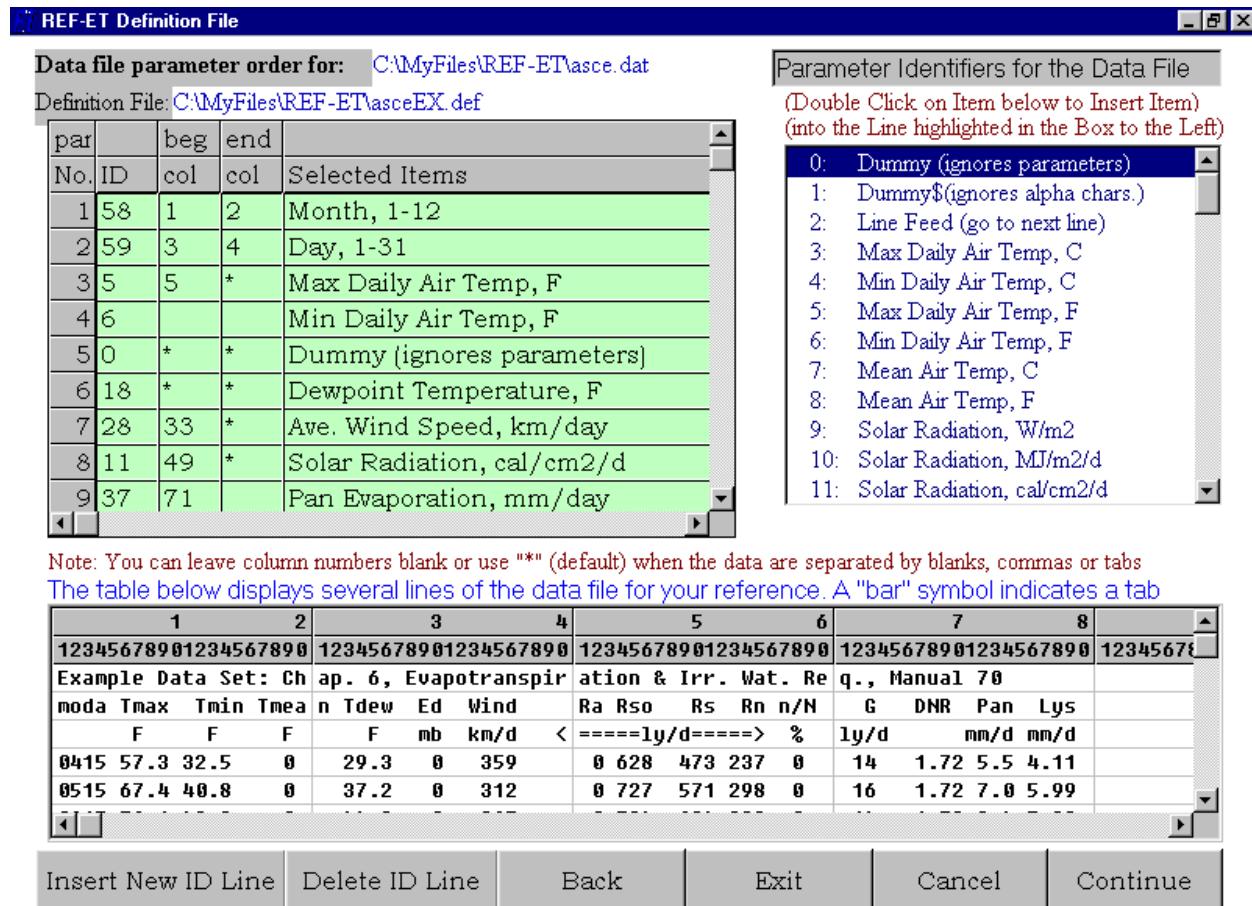


Figure 4. Editing screen for the definition file.

Specifying Where to Start and Where to Stop Reading a Parameter

Under most circumstances, weather data parameters that are contained in a data file are separated by blanks, commas or tabs. In these situations, and where all data columns are to be read from the data file, REF-ET is able to determine, automatically, where each column of data lies. Therefore, the user does not need to specify any beginning or ending column numbers in the "beg col" and "end col" columns in the upper left-hand of Fig. 4.

For example, in Fig. 4, the month and day of the month lie side by side in the data file in columns 1-2 and 3-4. There is no separation between month and day of month in the data file (see bottom portion of Fig. 4). Therefore, the user must instruct REF-ET to begin

reading the month in column 1 and to end in column 2. REF-ET is instructed to begin reading day of the month in column 3 and to end in column 4. For Maximum air temperature, REF-ET is instructed to begin reading in column 5 (to be sure to read any ">100 F" days. No ending column is given for maximum air temperature, since this data parameter is always followed by at least one blank (see Fig. 4). An asterisk ("*") or a blank indicate to REF-ET that it is to automatically determine the end of the temperature parameter.

The column numbers are entered on the screen by using the cursor keys to move from row to row or from column to column (using arrow keys on the keyboard or clicking with the mouse cursor). If data parameters in the weather data file happen to be separated by at least one blank or by a comma or both, then numbers identifying the beginning and ending columns **are not** required on the definition editor screen. When no beginning and ending column numbers are entered, the REF-ET program will attempt to differentiate between parameters in the data file by assuming that they begin and end with blanks or commas or tabs. In this case, the second and third ("Beg Col" and "End Col") can be left blank, or an asterisk (*) can be entered.

There happens to be an additional temperature variable in the ASCE.DAT weather data file (T_{mean}) that is not needed by the REF-ET program. Therefore, this variable is ignored. This is accomplished by specifying this variable as a "Dummy" variable (i.e., as parameter type "0"). The next desired variable in the ASCE.DAT file is dewpoint temperature. Dewpoint temperature data begins in column 22, but this does not need to be specified because dewpoint temperature is always preceded by at least one space. Therefore, REF-ET will always be able to find it. Since the T_{dew} value ends with a blank space in all instances, no ending column number is needed.

The next data parameter in the ASCE.DAT file is saturation vapor pressure at the dewpoint (termed "VP" in the data file). It was not desirable by the user to include this parameter in the REF-ET calculations. Therefore, it is also ignored by simply specifying the location of the next desireable parameter, which is wind speed, which begins in column 33. All types of numbers or even alphanumeric characters can be ignored by the REF-ET program in this manner. In summary, when the beginning column for a data item is entered, but the ending column is left blank or has an asterisk, then REF-ET will assume that the data item in the data file ends with a blank, tab or with a comma.

An alternative method for ignoring (skipping) numeric or alphanumeric data in the weather data file is to enter the parameter identification type as type 0 or 1, depending on whether the data file columns are numeric or alphanumeric characters. The "Dummy" designations of parameters 0 and 1 simply mean that the data will be read from the data file, but the values will be ignored.

Other Data File Reading Techniques

Data type 2 (line feed) can be used if data for the same time step happen to occupy more than one consecutive line within the data file. This may occur if REF-ET is used to read data from a file created by a Campbell Scientific datalogger (LOGAN90H.DAT for example).

The user can insert a new row of instructions (i.e., to read a new column in between two currently read columns) by pressing the "**Insert New ID Line**" button that is located at the bottom of the screen (Fig. 4). The cursor should be placed where the new line is desired before pressing the insert button. In the same way, the line that the cursor is resting on can be deleted by pressing the "**Delete ID Line**" button.

Warning: if a blank line has been inserted into the parameter list when the first editor screen is exited, the REF-ET program assumes that this blank line indicates the end of the data list, and all subsequent lines in the list will be ignored and will be deleted. Therefore, delete all blank inserted lines on the upper left-hand side of the screen that lie between valid definition rows before continuing on from this screen.

Pressing the "Back" button in Fig. 4 will take the user back to the data file opening dialog box. Pressing the "**Exit**" or "**Cancel**" buttons will terminate the program. Pressing the "**Continue**" button will take the user to the next definition file editing screen (you can come back again).

Data Parameter Definitions

There are 88 parameter types and measurement unit combinations defined for reading data into REF-ET. Hopefully these will cover the vast majority of data that will need to be read into REF-ET. These definitions are listed in the following Table 3.

Table 3. Data Parameter Types and units and identification numbers used by REF-ET to read weather data.

0	Dummy (ignores parameters)	41	Soil Heat Flux, W/m ²
1	Dummy\$(ignores alpha chars.)	42	Soil Heat Flux, MJ/m ² /hr
2	Line Feed (go to next line)	43	Soil Heat Flux, cal/cm ² /hr
3	Max Daily Air Temp, C	44	Net Radiation, MJ/m ² /day
4	Min Daily Air Temp, C	45	Net Radiation, cal/cm ² /day
5	Max Daily Air Temp, F	451	Net Radiation, kJ/m ² /day
6	Min Daily Air Temp, F	46	Net Radiation, W/m ²
7	Mean Air Temp, C	47	Net Radiation, mm/day
8	Mean Air Temp, F	48	Net Radiation, MJ/m ² /hr
9	Solar Radiation, W/m ²	49	Net Radiation, cal/cm ² /hr
10	Solar Radiation, MJ/m ² /d	491	Net Radiation, kJ/m ² /hr
11	Solar Radiation, cal/cm ² /d	492	Net Radiation, kJ/m ² /min
111	Solar Radiation, kJ/m ² /d	50	Albedo (if measured), dec.
12	Solar Radiation, mm/d	51	Albedo (if measured), %
13	Solar Radiation, MJ/m ² /hr	52	Lysimeter, mm/day
14	Solar Radiation, cal/cm ² /hr	53	Lysimeter, in/day
141	Solar Radiation, kJ/m ² /hr	54	Lysimeter, mm/period
142	Solar Radiation, kJ/m ² /min	55	Lysimeter, in/period
15	Percent Sunshine, n/N, dec.	56	Precipitation, mm
16	Percent Sunshine, n/N, %	57	Precipitation, inches
17	Dewpoint Temperature, C	58	Month, 1-12
18	Dewpoint Temperature, F	59	Day, 1-31
19	Min. Daily Rel. Humidity, %	60	Hour, 0-24
20	Max. Daily Rel. Humidity, %	601	Hour, 0000-2400
191	Min. Daily Rel. Humidity, dec.	602	Hour and Minute, 0000-2359
201	Max. Daily Rel. Humidity, dec.	61	Minute, 0-59
21	Ave. Rel. Humidity, %	62	Year, 00-99
211	Ave. Rel. Humidity, decimal	63	Year, 0000-2099
22	Ave. Vapor Press., kPa	64	Day of Year, 1-366
23	Ave. Vapor Press., mb	65	Measured Grass Ht, m
231	Ave. Absolute Humidity, kg/m ³	651	Measured Alfalfa Ht, m
232	Ave. Specific Humidity, kg/kg	652	Measured Grass Ht, cm
24	Wet Bulb Temperature, C	653	Measured Alfalfa Ht, cm
25	Dry Bulb Temperature, C	654	Measured Grass Ht, in.
26	Wet Bulb Temperature, F	655	Measured Alfalfa Ht, in.
27	Dry Bulb Temperature, F	66	Sunshine Hours (daily)
28	Ave. Wind Speed, km/day	67	Atmospheric Pressure, kPa
29	Ave. Wind Speed, m/s	68	Atmospheric Pressure, mb
30	Ave. Wind Speed, mi/day		
31	Ave. Wind Speed, km/hr		
32	Ave. Wind Speed, mi/hr		
321	Ave. Wind Speed, knots		
33	DayTime (7am-7pm) Wind, km/h		
34	DayTime (7am-7pm) Wind, m/s		
35	DayTime (7am-7pm) Wind, mi/h		
36	Day/Night Wind Ratio, decimal		
37	Pan Evaporation, mm/day		
38	Pan Evaporation, in/day		
39	Soil Heat Flux, MJ/m ² /day		
40	Soil Heat Flux, cal/cm ² /day		

Second Definition File Editor Screen

The second screen of the definition file editor is used to enter supplementary information that describes the weather measurement site and location. In addition, it is on this screen where the user specifies the number of lines at the beginning of the data file to skip before reading the actual weather data. If the definition file had been previously created, then the information that had been previously stored in the definition file will be displayed on the editor screen.

.. Description of the Weather Station and Data File

Data File is: C:\ZE\Ref-ET\ASCEmod\Version2\Package\Datasce.dat
Definition File is: C:\ZE\Ref-ET\ASCEmod\Version2\Package\DatasceEX.def

The anemometer height is: 3.66 meters (12.0) ft
The temperature/RH height is: 1.35 meters (4.4) ft
The weather station elevation is: 1195 meters (3920.6) ft
The weather station latitude is: 42.4 degrees (- for Southern)

(Data within box are Required only for hourly data)

The weather station longitude is: 114.5 degrees** W (E or W**) (Hint: 120 W)
Center of time zone longitude is: 105 degrees** W (E or W**) ← (The time zone longitude must be in multiples of 15 degrees)

The default Day/Night wind ratio is : 2 (2 if unknown*)
The weather site vegetation height : 12 m (0 if same as ref. or as ht. specified in the data file)
The green fetch on the Class A Pan : 1000 m (1000 if unknown*)
Initial Lines of the Data file to be skipped 3 Code for missing data (e.g. -999) -999

Description of the station and data (No more than 1000 characters)

Example Problem Set from the 1990 ASCE ET Manual (July at Kimberly) -Windows

For hourly data in U.S.A., Daylight Savings Time is Observed in Data Set

Note: Data marked with * are not required if there are only temperature data. **Req. only for hourly data.

Back Cancel Exit Continue

Figure 5. Second Definition Screen of REF-ET

The first ten lines of the screen in Fig. 5 describe the weather station location, including information on anemometer height, height of the temperature/RH sensor, weather station elevation, weather station latitude, weather station longitude and timezone center longitude (longitudes are only needed for computing hourly net radiation for hourly timesteps), default Day/Night wind ratio for the region (needed only for FAO-24 equations), the height of vegetation at the weather station, and the length of green fetch upwind of the evaporation Class A evaporation pan.

Station latitude is necessary for computing R_a used in the Hargreaves method and for computing net radiation (via R_{so}) and n/N. Station longitude is required only for estimating

hourly net radiation when hourly (or time steps less than 24 hours) data are read. For daily or monthly data, the longitude cells can be left as zero. The longitude of the center of the time zone is needed with hourly data to determine the sun angle for extraterrestrial radiation. For most locations of the globe, this longitude should be a multiple of 15° . It can be calculated by multiplying the time-lag of the time zone from Greenwich, England by 15° . For example, Kimberly, Idaho is 7 hours earlier than Greenwich. Therefore, the longitude for the Kimberly time zone (referred to as Mountain standard time) is $7 \times 15^{\circ} = 105^{\circ}$ West. For some countries that are a fraction of an hour different from Greenwich, for example, India, the fraction of hours should be multiplied by 15° . The blue tinted “hint” box to the right of the longitude entry attempts to provide a hint for the correct time. However, this hint may not be correct for locations that are near the boundaries of their time zone.

The user can indicate the number of lines to skip at the beginning of the weather data file as indicated in the screen of Fig. 5. Lines to be skipped include any header information. Header (labels) information needs to be skipped, otherwise, REF-ET will attempt to read these lines as data.

The user can enter a missing data code, for example –999 in Fig. 5, which instructs REF-ET to regard data as missing when the value read is equal to the value –999. One should be careful when using 0 for the missing value indicator, as this may incorrectly indicate a missing value for days when the measured parameter happens to have been 0.

The user is able to enter a multiline description of the data file and REF-ET “run” that will be printed in the intermediate and final result files and printouts. This is useful for documenting the particular computation procedure.

Pressing the “Back” button in Fig. 5 will take the user back to first definition screen. Pressing the “Exit” button will terminate the program. Pressing the or “Cancel” button will reset the data on the screen to what it was before any changes were made. Pressing the “Continue” button will take the user to the next definition file editing screen (you can come back again).

Selecting the Reference Type, Output Options and ET Equations

The third definition editing screen is shown in Fig. 6. This screen is used to select the type of output units to be used for the intermediate and final files and/or printouts, where the final ET_o or ET_r results are to be directed, which intermediate files are to be printed, and which ET equations are to be evaluated and the types of reference calculations to be made for each equation (grass or alfalfa).

English units include inches, $^{\circ}\text{F}$, and miles per day, although radiation parameters are expressed in calories per cm^2 (i.e., “Langley’s”). If the user selects “File and Screen” for output, he/she will be asked to indicate or to confirm a name for the output file on a later screen (Fig. 9). As indicated previously, the first intermediate file includes an “echo” of the data that have been read. Intermediate file 2 contains a series of intermediate parameters, for example Δ , λ , ρ , R_{so} , R_n , etc. The intermediate files are automatically named and are placed in the same folder that the original data file resides in.

A general ET reference ratio (ET_r/ET_o) is entered for converting those ET equations between the two reference types that are not defined for both reference types. For example, the FAO-56 PM equation is only defined for grass reference ET_o . Therefore, to predict alfalfa reference ET_r using the FAO-56 PM equation, it is multiplied by the ET_r/ET_o ratio inside of REF-ET. As described in a previous section, the ET_r/ET_o changes with climate and possible with time of year. Typical values for this ratio range from about 1.1 for humid and subhumid climates to 1.2 to 1.3 for semiarid and arid climates. An equation from FAO-56 for predicting ET_r/ET_o as a function of wind speed and relative humidity is contained in Appendix 4. The ET equation check boxes that have a “dot” beside them indicate that the equation is not defined for the particular reference type and therefore will utilize the specified ET_r/ET_o ratio to predict the reference ET.

Also on the definition screen in Fig. 6 are the standard heights to be used for the alfalfa and grass references in the ASCE Penman-Monteith equations (0.5 m is standard for alfalfa and 0.12 m is standard for grass). These two heights are used to change values calculated for aerodynamic and surface resistances used in the first ASCE PM (full) equation listed if they are different from 0.5 and 0.12 m. The heights specified in Fig. 6 are “overridden” by any reference vegetation heights that may be read in from the data file (new height(s) are read from each data line).

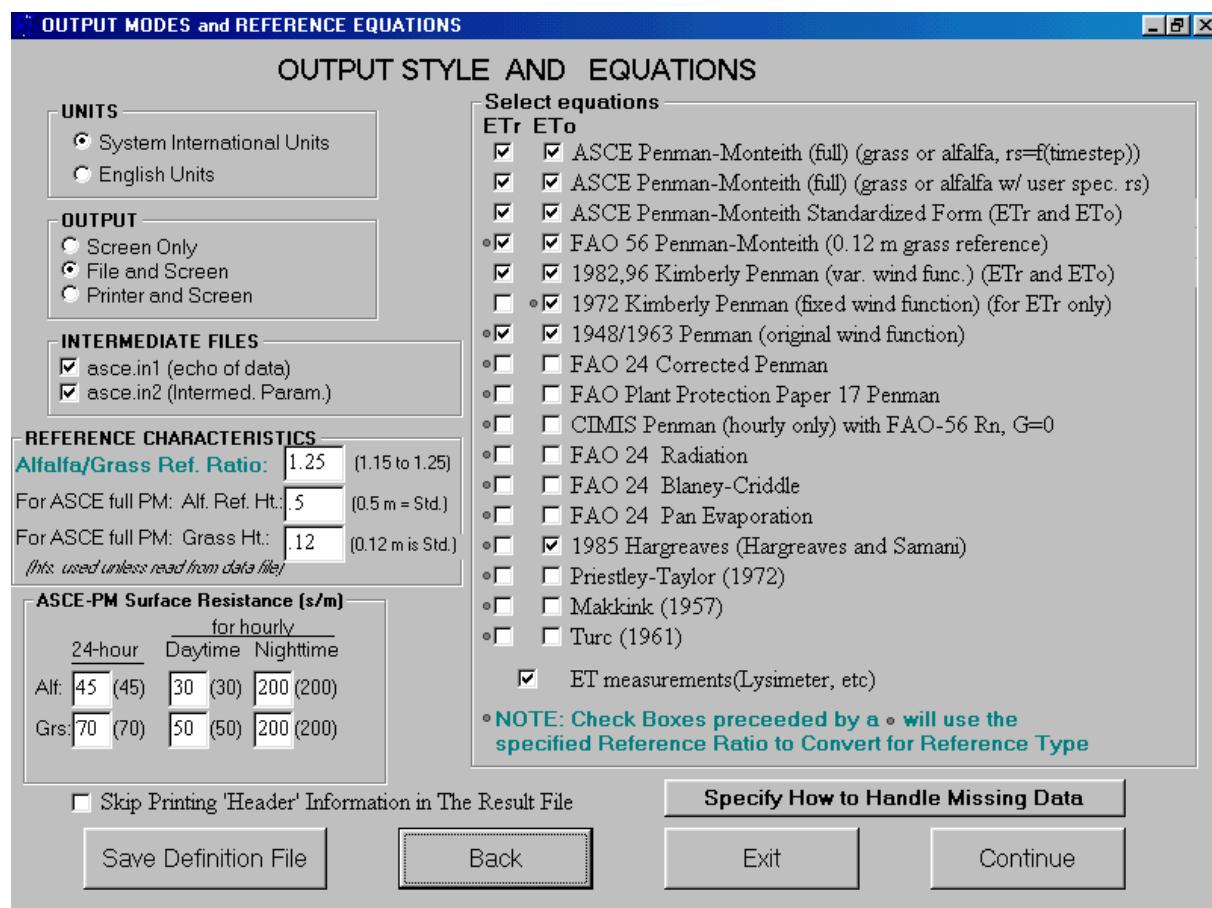


Figure 6. Third definition editing screen of REF-ET.

On the lower left-hand side of the screen shown in Fig. 6 are boxes where six values for surface resistance, r_s , can be entered. These are the values specified for alfalfa and grass reference types for 24-hour, hourly daytime, and hourly nighttime periods. These values for r_s are used with the second ASCE Penman-Monteith (full) equation presented in the equation list (see Fig. 6). These values for r_s correspond to the values for height of alfalfa and grass that are listed above the r_s values (see Fig. 6). If the height values are overridden during operation of REF-ET by reading new values for height from the data file, then the values for r_s for ASCE PM no. "2" (the "w/user spec. r_s " in Fig. 6) will be modified according to the change in leaf area index, LAI, using the ASCE algorithms for alfalfa and grass and the height value from the data file (if given). The Kim6971.dat file illustrates a situation in which vegetation height is read from the data file for each time step. These vegetation heights "override" the reference height specified in the definition file on the screen shown in Fig. 6.

Selection of Reference Equations and Reference Type

The user can select as many reference equations from the list presented in Fig. 6 as desired. In addition, both reference types may be selected for a single equation or only one type can be selected. The specific equations and reference types selected are stored in the definition file so that subsequent runs of REF-ET will "remember" which equations have been previously applied.

If lysimeter measurements (or other ET measurements) are to be read from the data file (as specified on the first definition shown in Fig. 4), then the user should check the "ET measurements" box shown in Fig. 6.

Estimation of Missing Data

When some parameters in the data file are missing (i.e., they are represented by the "code for missing data" indicated in Fig. 5), then REF-ET will attempt to predict the missing data. Also, if a parameter is not read from the file, for example, if there are no solar radiation data in the data file, then REF-ET can be instructed to predict the missing parameter using air temperature data. The only data that can not be predicted from other data, if missing, are air temperature data.

The specific means for predicting missing data are indicated by pressing the "Specify how to handle missing data" button in Fig. 6. Pressing this button brings up the "Missing Data" screen shown in Fig. 7.

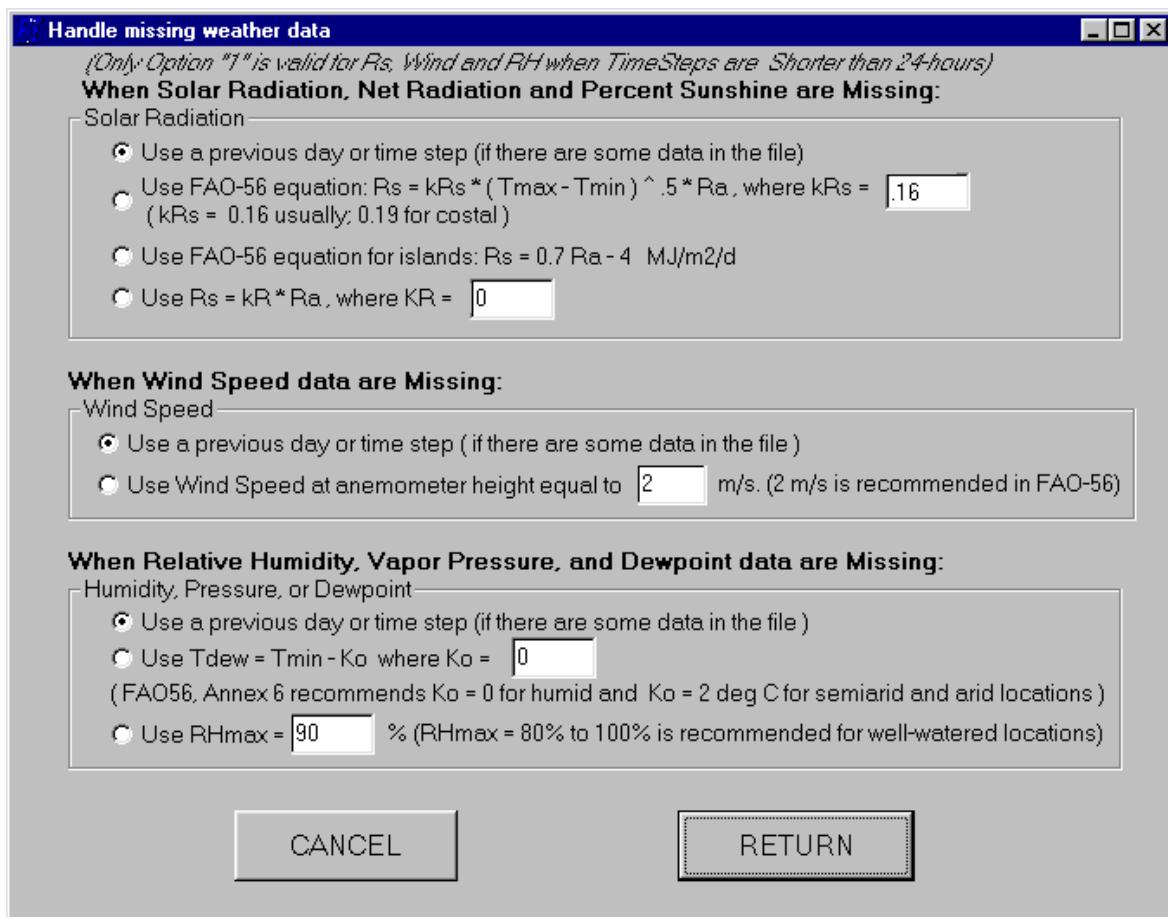


Figure 7. Screen for describing how to predict missing weather data.

Equations 3-3 and 3-4 of Appendix 3 are used to predict missing solar radiation data, R_s . Other options are to apply a constant ratio of R_s to R_a , which is the computed extraterrestrial radiation. A fourth option is to simply replicate the value of R_s that was recorded on the previous day or time step (if any).

Missing wind speed data can be predicted by assuming some constant value. FAO-56 recommends using $u_2 = 2$ to 3 m s^{-1} for agricultural areas. A table of guidelines on typical wind speed classes is given in Appendix 3.

Dewpoint temperature is estimated (if no type of humidity data is available for the time step) using minimum daily air temperature. This method does not work, of course, for hourly time steps. The value for K_o is recommended to be about $K_o = 2^\circ\text{C}$ for arid and semiarid climates and $K_o = 0^\circ\text{C}$ for humid and subhumid climates. An alternative is to presume that the maximum daily relative humidity is about 80 to 95% each night. Dewpoint temperature is then predicted from the RH_{max} estimate as described in Appendix 1. There are no means for predicting missing humidity data for hourly or shorter time steps other than using the value from the previous time step.

The user can return to the third definition screen (Fig. 6) by pressing the "Return" button on the Fig. 7 screen.

Soil Heat Flux and Net Radiation Measurements

Soil heat flux can be read from the data file. Otherwise, it is predicted as described in Appendix 1. If the user wishes to force monthly, daily or hourly soil heat flux to be zero, then the user should direct the definition file to read G from a blank column in the data file.

If values for net radiation are not entered into REF-ET, then these are estimated using the methods of FAO-56 and Wright (1982), based on daily solar radiation, maximum and minimum air temperature, and vapor pressure. If albedo is not read from the file, then it is estimated as 0.23 for the FAO-56 R_n or it is computed using the Wright (1982) equation for the Wright (1982) R_n .

Other Calculations

Crop height can be entered for each day or time step in the data file for when these heights are known for either the grass or alfalfa reference crop. These measurements will then override the reference height parameter listed on the third screen of the definition file (Fig. 6). However, if the intent is to produce a "standard" reference estimate using the "full" ASCE PM equation, then 0.5 m for alfalfa and 012 m for grass should be utilized.

Mean daily temperature is used to compute latent heat of vaporization and slope of the saturation vapor pressure curve for 24-hour and monthly time steps. Daily mean temperature, if not entered, is computed as the average of maximum and minimum air temperature.

When maximum and minimum air temperature are not entered, then they are assumed to both be equal to mean air temperature, for purposes of calculating net radiation and VPD. This is true for hourly data, also.

e_a (average saturation vapor pressure of air) is always computed at mean air temperature for the 1963 and FAO-24 Penman equations and as the average of $e^o(T_{max})$ and $e^o(T_{min})$ for the Kimberly Penmans and for the FAO and ASCE Penman-Monteith equations.

The CIMIS Penman equation (used in the California Irrigation Management Information Service program and developed by W.O. Pruitt of Univ. of California, Davis) is only applied hourly. This equation has a separate daytime and nighttime empirical wind function. In REF-ET, the CIMIS Penman is applied using net radiation (if not read from the data file) computed following FAO-56 procedures and with hourly soil heat flux set equal to 0, following standard CIMIS procedure.

Estimation of the Timestep

REF-ET can compute reference ET on monthly, daily, or hourly (or less) time steps. Monthly and daily computations are presented as mm/day and computations for time steps of less than 24-hours are presented as mm/hour. REF-ET assumes that time steps are monthly or daily unless the time parameters 60 (Hour) or 61 (Minute) are read from the data file. Either the day of the year (64) or Month (58) and Day of Month (59) MUST be read for each line of the data file (even for hourly data), as this information is needed to compute extraterrestrial radiation, net radiation, and the coefficients for the wind functions of the 1982 and 1996 Kimberly Penman methods for each specific day of the year.

If hours or minutes are read from the file and these values are less than 24-hours apart, then REF-ET assumes that the data and computation time steps are for less than 24-hour periods and ET results are printed in mm/hr and radiation units are expressed as W/m². If the Day of the Month is not given or is zero, REF-ET assumes that the data are monthly data and sets the Day of the Month equal to 15. Computations for monthly data are the same as for daily data.

Saving the Definition File Data

When the user leaves the third definition file editing screen (Fig. 6) by pressing the "Continue" button, he/she is asked whether he/she wishes to save the definition file. If the answer is no, then any changes to the definition file will not be saved to disk. However, any changes to the definition information will still be used in the subsequent processing of weather data. If some changes were made to the definition information that are unacceptable, then the user should press the "Cancel" button on screen three (Fig. 6) and start over.

If the user desires to save the changes made to the definition information, then the file save dialog box shown in Fig. 8. is displayed. The user can change the name of the definition file, or he/she can use the name that was previously specified (or opened). If the user selects "Cancel", then no changes will be made to the definition file. However any changes made will be applied in the subsequent processing unless the user starts over.

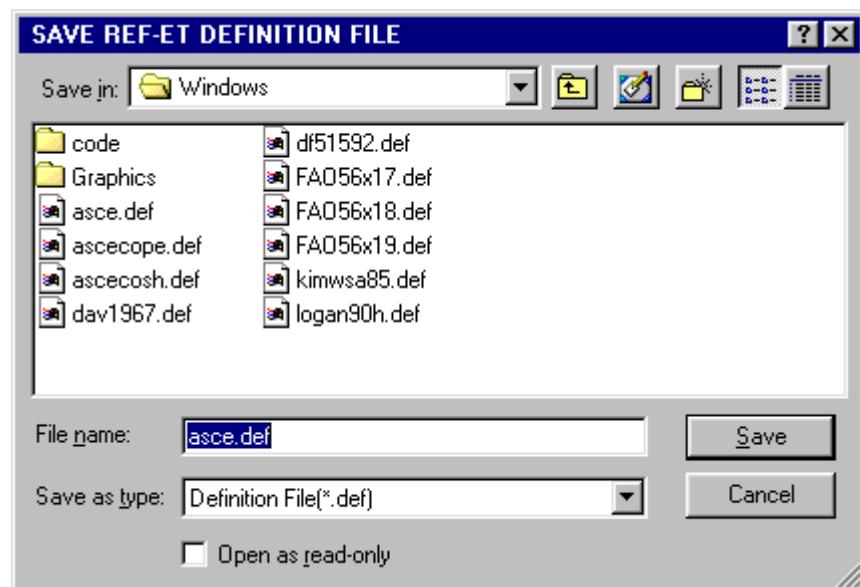


Figure 8. Dialog box for saving the Definition File.

After saving the definition file, the user is prompted, via the dialog box shown in Fig. 9, to specify the name for the output file into which to save results of the reference ET calculations, if the user specified the “print” option on the third screen of the definition editor (Fig. 6). The default name for the output file is the same as the original data file with the extension “.out”. The user can change or modify this name.

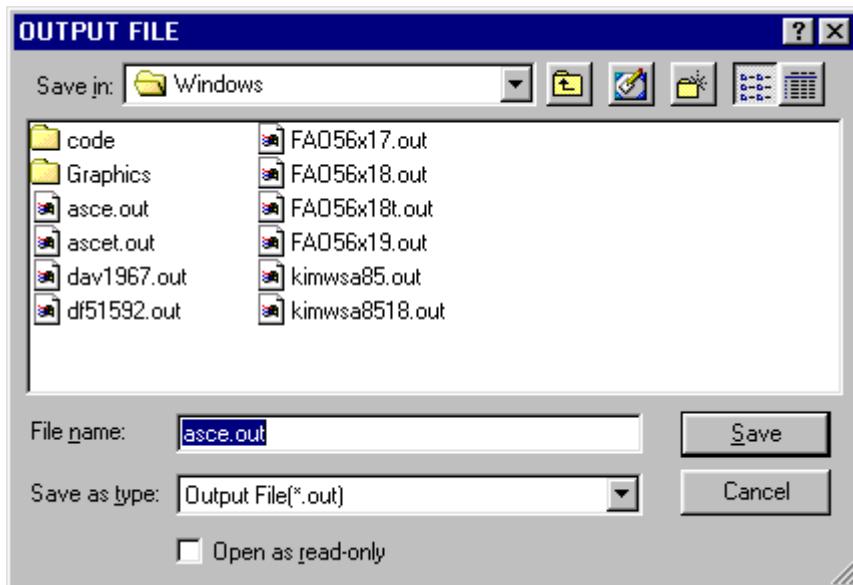


Figure 9. Dialog box for saving REF-ET results.

Processing of the Weather Data File

Following the saving of (or not saving) the definition (and output) files, REF-ET begins to process the weather data file. The first screen presented by REF-ET “echoes” the first lines of the data file that were skipped, as shown in Fig. 10, according to the instructions provided by the user in Fig. 5. The user is prompted on this screen to “Press any key to CONTINUE”.

Actual processing of each line of the data file will begin after the user presses a key on the keyboard. The line number of each line of the data file being processed will be displayed as REF-ET computes parameters and reference ET for that line. Final results are only presented after all lines of the data file have been processed.

```
Output screen: C:\Ricks\REF-ET\Windows\asce.dat
These Initial Lines of File: C:\Ricks\REF-ET\Windows\asce.dat
have been skipped:

Example Data Set: Chap. 6, Evapotranspiration & Irr. Wat. Req., Manual 70
moda Tmax Tmin Tmean Tdew Ed Wind Ra Rso Rs Rn n/N G DNR Pan Lys
F F F F mb km/d <=====ly/d=====> % ly/d mm/d mm/d

PRESS any key to CONTINUE
```

Figure 10. First result file displayed by REF-ET showing skipped data lines.

Final Results

The final results are displayed in a second window as illustrated in Fig. 11. The results shown in Figure 11 can be scrolled up or down for long data files. Specific definitions for each reference ET equation displayed can be found in the header of the output data file (if an output file was specified to be created) or on the result printout (if selected).

Pressing the "Continue" key on the output screen shown in Fig. 11 will take the user back to the beginning of the REF-ET program. Pressing "End" will end the program.

Specific definitions of headings of final calculations are written in the disk files and results that are written to a printer (see section following the list of references for examples of these files).

If more ET equations are selected than can be presented on the output screen shown in Fig. 11, then scroll bars are included in the header and data windows so that the boxes can be scrolled to the right. Unfortunately, the scrolling of the two boxes can not be tied together, so that the user must scroll each one separately.

Only the first 200 to 500 lines of data are presented in the output box shown in Fig. 11. The balance of the data is placed directly into a disk file or printed, depending on the option selected by the user.

Output screen: C:\ZE\Ref-ET\ASCEmod\Version2\Package\Data\asce.dat

REF-ET FINAL REFERENCE EVAPOTRANSPIRATION CALCULATIONS (for first 200 - 500 lines or so)

Mo	Day	Yr	Tmax	Tmin	Rs	Wind	DewP	ASCE	ASCE	ASCE	ASCE	ASCE	FAO	FAO	1982	1	
								PM	PM	PMrs	PMrs	stPM	stPM	56PM	56PM	KPen	K
								ETr	ETo	ETr	ETo	ETr	ETo	ETr	ETo	ETr	E
			C	C	MJ/m ²	m/s	C	mm/d	m								
4	15	0	14.1	.3	19.8	4.2	-1.5	4.73	3.46	4.72	3.46	4.73	3.42	4.28	3.42	4.26	3.
5	15	0	19.7	4.9	23.9	3.6	2.9	6.05	4.55	6.04	4.55	6.05	4.50	5.63	4.50	5.82	4.
6	15	0	24.5	9.3	26.1	3.1	6.8	7.13	5.50	7.12	5.50	7.11	5.44	6.80	5.44	7.26	5.
7	15	0	29.5	11.8	27.0	2.5	9.7	7.76	6.08	7.75	6.09	7.73	6.00	7.50	6.00	7.92	6.
8	15	0	28.7	10.7	22.9	2.5	8.2	7.19	5.50	7.19	5.50	7.16	5.41	6.76	5.41	6.93	6.
9	15	0	23.3	5.9	18.4	2.7	4.0	5.73	4.21	5.72	4.21	5.71	4.14	5.18	4.14	5.22	4.
10	15	0	16.4	.7	12.8	2.8	-.5	3.83	2.68	3.82	2.68	3.82	2.63	3.29	2.63	3.20	2.

Continue End

Figure 11. Example results from REF-ET that are displayed on the screen.

Graphical Comparisons of Reference ET Estimates

No provision is made within REF-ET for displaying ET information graphically. This can be done by the user by storing final ET results to a disk file (see Fig. 6) and then importing the disk file into a spreadsheet program. The data should be imported as “ “ delimited (i.e., blank delimited) data.

ASCE.DAT Example Data File

The following table is the ASCE.DAT data file that was used by REF-ET to generate the following Intermediate File and Results File.

Example Data Set: Chap. 6, Evapotranspiration & Irr. Wat. Req., Manual 70															
moda	Tmax	Tmin	Tmean	Tdew	VP	Wind	Ra	Rso	Rs	Rn	n/N	G	DNR	Pan	Lys
F	F	F	F	F	mb	km/d	<=====y/d=====>	%	ly/d			mm/d	mm/d	mm/d	mm/d
0415	57.3	32.5	0	29.3	0	359	0	628	473	237	0	14	1.72	5.5	4.11
0515	67.4	40.8	0	37.2	0	312	0	727	571	298	0	16	1.72	7.0	5.99
0615	76.1	48.8	0	44.2	0	267	0	784	624	328	0	14	1.72	8.4	7.39
0715	85.1	53.3	69.2	49.4	12	214	961	755	644	333	82.5	5	1.72	8.4	7.87
0815	83.7	51.3	0	46.8	0	212	0	665	546	278	0	-10	1.72	7.4	6.78
0915	73.9	42.6	0	39.2	0	232	0	547	439	207	0	-19	1.72	5.5	5.11
1015	61.5	33.2	0	31.1	0	243	0	408	306	118	0	-5	1.72	3.6	3.15

Examples of Intermediate File 2 and Final Results File

Intermediate File 2.

The following Intermediate Data File #2 Example is based on the ASCE.DAT file. The following text and header information is taken directly from the .IN2 file.

Intermediate Data File #2 From Climatic Data File: C:\ZE\Ref-ET\ASCEmod\Distrl\Data\asce.dat

Computed by the REF-ET program Ver. 2.0 Windows on Date: 02-04-2000 Time: 10:47 am

(SI Units)

Definition of Parameter Headings:

Mo	-- Month of Year (1 - 12)
Da	-- Day of Month (1 - 31)
Year	-- Year (if given)
DoY	-- Day of Year (1 = Jan 1, 365 = Dec 31)
Tave	-- Average of daily maximum and minimum air temperature
e(tx)	-- Saturation vapor pressure at maximum air temperature
e(tn)	-- Saturation vapor pressure at minimum air temperature
e(ta)	-- Saturation vapor pressure at mean air temperature
es	-- Saturation vapor pressure used in Kimberly, ASCE and FAO56 Eqns
ea	-- Atual vapor pressure of the air (Saturation vapor pressure at dew point)
albedo	-- (Wr82) Ave. 24-hour albedo based on Wright (1982)
dec	-- Declination of earth relative to the sun
dr	-- Inverse relative distance from the earth to the sun
omega	-- Sunset hour angle (radians) or sun hour angle at midperiod if hourly data (Potential Hours of Sunshine (N) = omega*24/Pi for daily)
Ra	-- Extraterrestrial radiation
Rso75	-- Clear sky solar radiation computed as 0.75*Ra for daily
Rso56a	-- Based on most simple Rso equation in Allen(1996) and FAO56 Rso56a = (0.75 + 2 E-5 elevation)Ra where elev is in m
Rso56c	-- Based on most complete Rso equation in Allen(1996) and FAO56 Rso56c = (KB + KD)Ra w/ corrected KD = 0.35 - 0.36 KB for KB > 0.15
Rs/Rso56a	-- Ratio of Rs(measured)/Rs for clear day where Rso is Rso56a method
Rs/Rso56c	-- Ratio of Rs(measured)/Rs for clear day where Rso is Rso56c method
a1	-- Coefficient used in net radiation estimation by Wright (1982)
a	-- coefficient used in net radiation method by Wright (1982)
b	-- coefficient used in net radiation method by Wright (1982)
Rbo W82	-- Net outgoing long-wave radiation on a clear day (Wright, 1982)
Rnl W82	-- Net outgoing long-wave radiation (Wright, 1982)
Rn82	-- Net radiation measured or calculated using Wright (1982)
Rbo F56	-- Net outgoing long-wave radiation on a clear day (FAO-56)
Rnl F56	-- Net outgoing long-wave radiation (FAO-56)
Rn56	-- Net radiation calculated using FAO-56 procedures Both Rn82 and Rn56 use Rso56a for 24-hour and Rso56c for hourly
Gmeas	-- Soil heat flux (measured)
G82	-- Soil heat flux (calculated using Wright (1982) (for 24-h))
G56	-- Soil heat flux calculated using FAO-56 Calc. G = 0 for 24-hr, =.1Rn,.5Rn (day,night)for hrly grass = f(T) for monthly
GASCE	-- Calc. G = 0 for 24-hr, =.04Rn,0.2Rn (day,night) for hrly alf., = f(T) for monthly
L.Heat	-- Latent heat of vaporization
P	-- Mean atmospheric pressure (estimated)

Delta	-- Slope of the saturation vapor pressure curve at mean air temp
Gamma	-- Psychrometric constant
Gam56	-- Psychrometric constant computed by FAO-56 = 0.665 E-3 P
T'	-- Virtual air temperature
Density	-- Density of air
Aw-Kpen	-- Aw wind coefficient for 1982 Kimberly Penman
Bw-Kpen	-- Bw wind coefficient for 1982 Kimberly Penman
Awg-Kpen	-- Aw wind coefficient for Kimberly Penman, grass wind function (Wright, 1996)
Bwg-Kpen	-- Bw wind coefficient for Kimberly Penman, grass wind function (Wright, 1996)
U24@2m	-- Twenty-four hr wind speed adjusted to 2 m height over grass or specified veg. ht.
U24r@2m	-- Twenty-four hr wind speed adjusted to 2 m height over alfalfa or specified veg. ht.
Ud@2m	-- Daytime (7am-7pm) wind speed at 2 meters height over grass or specified surface
m.grs.ht	-- Measured height for grass read from the data file and used in the first two ASCE PM equations
m.alf.ht	-- Measured height for alfalfa read from the data file and used in the first two ASCE PM equations
ra70o	-- Aerodynamic resistance to vapor,sensible heat transport for grass (ASCE Man.70)
ra70r	-- Aerodynamic resistance to vapor,sensible heat transport for alfalfa (ASCE Man.70)
rsoASCE	-- Bulk surface (i.e., stomatal or canopy)resistance for grass (ASCE Task Committee))
rsrASCE	-- Bulk surface (i.e., stomatal or canopy)resistance for alfalfa (ASCE Task Committee))
rsouser	-- Bulk surface (i.e., stomatal or canopy)resistance for grass (user spec. for given ht)
rsruser	-- Bulk surface (i.e., stomatal or canopy)resistance for alfalfa (user spec. for given ht)

Note: ra70, and rsASCE are computed from height specified in definition file or in data file using ASCE 70 algorithms (Allen et al., 1989).

Standard value for 0.12 m grass is 70, 50, 200 s/m for 24-hour, daytime, nighttime

Standard value for 0.50 m alfalfa is 45, 30, 200 s/m for 24-hour, daytime, nighttime.

rs_u is computed from the rs specified in the definition file and its value is modified relative to ht in data file if specified, as rs_u = rs_sp * LAI_sp/LAI_d where rs_sp is rs spec. in def. file and LAI_sp is based on ht. spec. in def file and LAI_d is based on ht spec. in data file (if present).

FAO24Pn-c	--correction factor for FAO-24 Penman
FAO24Rad-b	--correction factor for FAO-24 Radiation Method
FAO24BC-a	--correction factor a for FAO-24 Blaney-Criddle
FAO24BC-b	--correction factor b for FAO-24 Blaney-Criddle
N	-- Possible hours of sunshine per day
n/N	-- percent possible sunshine (decimal)
p BC	-- daily percentage of annual sunshine hours for Blaney-Criddle
FAO24 kp	-- correction factor for FAO-24 Pan Evaporation Method
DNR	-- Day/Night Wind ratio (7am - 7pm) (limited to 1-4 range)
RHmn	-- minimum daily relative humidity
RHmean	-- mean relative humidity (ave of RHmx,RHmn)
RHmx	-- maximum daily relative humidity (RHmx is limited to <= 100 in computations)

NOTE: Some parameters may have values of zero if these parameters were not calculated (such as a1 if Rn was read rather than calculated)

(The following “groups” of parameters are all on one line in the .IN2 file)

Mo	Da	Year	DoY	Tave	e(tx)	e(tn)	e(ta)	es	ea	albedo	dec	dr	omega
				C	kPa	kPa	kPa	kPa	kPa	Wr82			rad.
4	15	0	105	7.2	1.60	.62	1.01	1.11	.55	.269	.16	.99	1.72
5	15	0	135	12.3	2.29	.87	1.43	1.58	.75	.243	.33	.98	1.89
6	15	0	166	16.9	3.07	1.17	1.93	2.12	.99	.231	.41	.97	1.98
7	15	0	196	20.7	4.12	1.39	2.44	2.76	1.20	.234	.38	.97	1.94
8	15	0	227	19.7	3.94	1.29	2.30	2.62	1.09	.254	.24	.98	1.80
9	15	0	258	14.6	2.86	.93	1.66	1.89	.81	.284	.04	.99	1.61
10	15	0	288	8.5	1.86	.64	1.11	1.25	.59	.314	-.17	1.01	1.42

Ra	Rso75	Rso56a	Rso56c	Rs/ Rso56a	Rs/ Rso56c
<-----MJ/m ² /day----->					
34.0	25.5	26.3	26.6	.754	.745
39.5	29.6	30.6	31.1	.782	.769
41.9	31.4	32.4	32.9	.806	.793
40.8	30.6	31.6	31.9	.854	.846
36.2	27.2	28.1	28.1	.815	.813
29.0	21.8	22.5	22.3	.818	.825
21.2	15.9	16.4	16.0	.780	.802

a1	a	b	Rbo W82	Rnl W82	Rn82 F56	Rbo F56	Rnl F56	Rn56	Gmeas	G82	G56	GASCE
<=====MJ/m ² /day=====>												
.286	1.126	-.07	5.6	4.3	10.1	7.2	4.8	10.5	0.0	0.0	0.0	0.0
.322	1.126	-.07	6.6	5.3	12.8	7.1	5.0	13.4	0.0	.7	.7	.7
.355	1.126	-.07	7.6	6.3	13.8	7.0	5.2	14.9	0.0	.6	.6	.6
.354	1.126	-.07	7.4	6.6	14.0	6.9	5.5	15.3	0.0	.5	.5	.5
.319	1.126	-.07	6.3	5.4	11.7	7.0	5.3	12.3	0.0	-.1	-.1	-.1
.284	1.126	-.07	5.3	4.6	8.6	7.2	5.4	8.7	0.0	-.7	-.7	-.7
.266	1.126	-.07	5.0	4.0	4.8	7.2	5.1	4.8	0.0	-.8	-.8	-.8

L.Heat P MJ/Kg	P kPa	Delta <====kPa/C=====>	Gamma	Gam56	T'	Density K	Aw Kpen	Bw Kpen	Awg KPen	Bwg Kpen
2.483	87.7	.0695	.0575	.0583	281.0	1.089	.75	.62	.37	.34
2.471	87.7	.0940	.0578	.0583	286.4	1.068	1.31	.66	.62	.40
2.460	87.7	.1222	.0581	.0583	291.3	1.050	1.78	.74	.88	.55
2.451	87.7	.1500	.0583	.0583	295.4	1.036	1.60	.85	.72	.75
2.453	87.7	.1426	.0582	.0583	294.3	1.039	.99	.94	.42	.86
2.466	87.7	.1072	.0580	.0583	288.8	1.059	.56	.94	.31	.76
2.480	87.7	.0754	.0576	.0583	282.4	1.083	.43	.86	.30	.56

U24	U24r	Uday	m.grs	m.alf	rao	rar	rs_o	rs_r	rs_o	rs_r
@2m	@2m	@2m	ht.	ht.	ASCE	ASCE	ASCE	ASCE	user	user
m/s	m/s	m/s	m	m	s/m	s/m	s/m	s/m	s/m	s/m
3.7	3.7	4.9	0.00	0.00	53	31	70	45	70	45
3.2	3.2	4.3	0.00	0.00	61	36	70	45	70	45
2.7	2.7	3.7	0.00	0.00	71	42	70	45	70	45
2.2	2.2	2.9	0.00	0.00	89	52	70	45	70	45
2.2	2.2	2.9	0.00	0.00	90	53	70	45	70	45
2.4	2.4	3.2	0.00	0.00	82	48	70	45	70	45
2.5	2.5	3.3	0.00	0.00	78	46	70	45	70	45

FAO24 Pn-c	FAO24 Rad-b	FAO24 BC-a	FAO24 BC-b	N	n/N	p BC	FAO24 kp	DNR (1-4)	RH mn	RH mean	RH mx
				hrs		%			%	%	%
1.029	1.004	-1.93	1.498	13.16	.67	.30	.679	2.00	34	61	88
1.089	.996	-1.98	1.519	14.41	.71	.33	.774	2.00	33	60	87
1.106	.992	-2.02	1.524	15.09	.75	.34	.785	2.00	32	58	84
1.127	.974	-2.11	1.574	14.81	.82	.34	.797	2.00	29	58	87
1.084	.983	-2.05	1.539	13.73	.76	.31	.797	2.00	28	56	85
1.044	.979	-2.05	1.551	12.27	.77	.28	.788	2.00	28	58	88
.972	.962	-1.98	1.478	10.82	.71	.25	.788	2.00	32	62	92

Example of Final Results

(from the ASCE.DAT data file)

REF-ET REFERENCE EVAPOTRANSPIRATION CALCULATOR Ver. 2.0 Windows

Computer Program Supplement to ASCE Manual 70:
EVAPOTRANSPIRATION AND IRRIGATION WATER REQUIREMENTS
M.E. Jensen, R.D. Burman and R.G. Allen, Editors, 1990
and FAO Irrigation and Drainage Paper No. 56:
CROP EVAPOTRANSPIRATION: Guidelines for Computing Crop Water Req.
R.G. Allen, L.S. Pereira, D. Raes, M. Smith. 1998
and to calculate ASCE Standardized Reference ET as recommended
by the 1999/2000 ASCE Task Committee on Standardized ET

REF-ET was programmed at Utah State University
and at the University of Idaho. All Rights are Reserved.

Results from Data File: "C:\ZE\Ref-ETASCEmod\Dist\Data\asce.dat"
Computed on Date: 02-04-2000 Time: 10:47 am

This version of REF-ET can calculate and print both Grass and Alfalfa Reference ET
in the same printout or file

The Description of the Weather Data Set is:

"Example Problem Set from the 1990 ASCE ET Manual (July at Kimberly) -Windows

This definition file describes the data format for the data file:
asce.dat"

The anemometer height is: 3.66 meters (12.01 feet)
The temperature/RH height is: 1.35 meters (4.43 feet)
The weather station elevation is: 1195 meters (3921 feet)
The weather station latitude is : 42.4 degrees
The weather station longitude is: 114.5 degrees West
The time zone longitude is: 120 degrees West
The default day/night wind ratio: 2
Daylight Savings time is recognized and adjusted for following U.S. traditions
The alfalfa/grass ref. ratio is: 1.25
The alfalfa reference height is: 0.5 meters
The grass reference height is: 0.12 meters
The weather vegetation height is: 0.12 meters (0 = same as ref crop)

A user-entered alfalfa surface resist. (for the above alfalfa ht.) is: 45 s/m
A user-entered grass surface resist. (for the above grass ht.) is: 70 s/m
The green fetch of the Pan (A) is: 1000 meters
The indicator for missing data is: -999

KEY for Headings:

Tmax	-- Reported 24-hr maximum air temperature
Tmin	-- Reported 24-hr minimum air temperature
Rs	-- Reported average solar radiation (global shortwave)
Rn	-- Reported (user supplied) net radiation
n/N	-- Reported percent hours of sunshine
Wind	-- Reported average wind speed at 3.66 meters
DewP	-- Reported or calculated dewpoint temperature
ASCE-PM	-- ASCE Penman-Monteith (Allen et.al, 1989, ASCE, 1990) rs24 = 70 s/m for ET _o and 45 s/m for ET _r rshrl = 50 s/m for ET _o daytime and 200 s/m nighttime rshrl = 30 s/m daytime and 200 s/m nighttime for ET _r . above values for rs are for 0.12 m grass and 0.5 m alfalfa the values for rs change with change in specified heights
ASCE-PMrs	-- ASCE Penman-Monteith (Allen et.al, 1989, ASCE, 1990) with user specified surface resistance (rs) as specified above for 24-hour, daytime and nighttime for ET _o (grass) and ET _r (alfalfa). above values for rs are for grass and alfalfa heights specified the values for rs change with change in specified heights
ASCE-stPM	-- ASCE Penman-Monteith--Standardized Form (1999, 2000) in FAO-56 style reduced form for 0.12 m grass or 0.5 m alfalfa rs24 = 70 s/m for ET _o and 45 s/m for ET _r rshrl = 50 s/m daytime and 200 s/m nighttime for ET _o rshrl = 30 s/m daytime and 200 s/m nighttime for ET _r
FAO56-PM	-- FAO56 Penman-Monteith for 0.12 m grass ET _o with rs = 70 s/m (ET _o)
1982-Kpen	-- 1982 Kimberly Penman ET _r (Wright, 1982; 1987) w/Rn82, G82 (ET _r) -- for ET _o , the variable grass wind function by Wright (1996)is used
1972-Kpen	-- 1972 Kimberly Penman ET _r (Wright, 1972) w/Rn72, G82 (ET _r)
1948-Pen	-- 1948 or 1963 Version of Penman (Penman, 1948,1963) w/Rn56, G56 (ET _o)
1985-Harg	-- 1985 Hargreaves (Hargreaves et al, 1985) (ET _o)
ET-meas	-- Lysimeter or other-Measured Evapotranspiration

RESULTS (SI Units): (*the following two “groups” are presented on one line in REF-ET output*)

Mo	Day	Yr	Tmax	Tmin	Rs	Wind	DewP												
			C	C	MJ/m ²	m/s	C												
4	15	0	14.1	.3	19.8	4.2	-1.5												
5	15	0	19.7	4.9	23.9	3.6	2.9												
6	15	0	24.5	9.3	26.1	3.1	6.8												
7	15	0	29.5	11.8	27.0	2.5	9.7												
8	15	0	28.7	10.7	22.9	2.5	8.2												
9	15	0	23.3	5.9	18.4	2.7	4.0												
10	15	0	16.4	.7	12.8	2.8	-.5												
ASCE	ASCE	ASCE	ASCE	ASCE	FAO	FAO	1982	1996	1972	1948	1948	1985							
PM	PM	PMrs	PMrs	stPM	stPM	56PM	56PM	KPen	KPen	KPen	Pen	Pen	Harg	Meas.					
ETr	ETr	ETr	ETr	ETr	ETr	ETr	ETr	ETr	ETr	ETr	ETr	ETr	ET						
mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d					
4.73	3.46	4.72	3.46	4.73	3.42	4.28	3.42	4.26	3.31	4.15	4.92	3.94	2.91	4.11					
6.05	4.55	6.04	4.55	6.05	4.50	5.63	4.50	5.82	4.57	5.08	6.25	5.00	4.25	5.99					
7.13	5.50	7.12	5.50	7.11	5.44	6.80	5.44	7.26	5.89	5.80	7.38	5.90	5.29	7.39					
7.76	6.08	7.75	6.09	7.73	6.00	7.50	6.00	7.92	6.66	6.15	7.89	6.31	6.19	7.87					
7.19	5.50	7.19	5.50	7.16	5.41	6.76	5.41	6.93	6.08	5.58	7.00	5.60	5.41	6.78					
5.73	4.21	5.72	4.21	5.71	4.14	5.18	4.14	5.22	4.56	4.43	5.32	4.25	3.66	5.11					
3.83	2.68	3.82	2.68	3.82	2.63	3.29	2.63	3.20	2.56	2.93	3.34	2.67	2.06	3.15					

Errata to Various Publications

Errata to ASCE Manual 70 that should be noted if using it as a source of equations

1. Correction of hourly time calculation in hourly extraterrestrial calculation. In ASCE Manual 70, Ls-L1 in Equation B2.4 of manual 70 should be in degrees when using the coefficient .066667.

Errata to FAO-56 that should be noted if using it as a source of equations

1. Equation 3-20 on page 227 has been updated since publication of FAO-56. The “0.33” coefficient should be changed to “0.36” for the computation of clear sky solar radiation.

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Appendix 1

ASCE and FAO Penman-Monteith Equations and Kimberly Penman equation

This appendix introduces the equations used to compute all parameters for the ASCE Penman-Monteith equation and the FAO-56 Penman-Monteith equation which is a reduced form for standard crop height conditions. The 1982 Kimberly Penman equation is also described.

The Penman-Monteith form of the combination equation is:

$$ET_o = \left(\frac{\Delta(R_n - G) + K_{time} \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a} \right)} \right) / \lambda \quad (1)$$

where

- ET_o is the reference evapotranspiration, mm d⁻¹ or mm h⁻¹
- R_n is the net radiation, MJ m⁻² d⁻¹ or MJ m⁻² h⁻¹
- G is the soil heat flux, MJ m⁻² d⁻¹ or MJ m⁻² h⁻¹
- $(e_s - e_a)$ represents the vapor pressure deficit of the air, kPa
- e_s is saturation vapor pressure of the air, kPa
- e_a is the actual vapor pressure of the air, kPa
- ρ_a is the mean air density at constant pressure, kg m⁻³
- c_p is the specific heat of the air, MJ kg⁻¹ °C⁻¹
- Δ is the slope of the saturation vapor pressure temperature relationship, kPa °C⁻¹
- γ is the psychrometric constant, kPa °C⁻¹
- r_s is the (bulk) surface resistance, s m⁻¹
- r_a is the aerodynamic resistance, s m⁻¹
- λ is latent heat of vaporization, MJ kg⁻¹
- K_{time} is a units conversion, equal to 86,400 s d⁻¹ for ET in mm d⁻¹ and equal to 3600 s h⁻¹ for ET in mm h⁻¹

Required Data for 24-hour or longer time steps:

T_{max}	maximum daily air temperature, °C
T_{min}	minimum daily air temperature, °C
T_{dew}	mean daily or "early morning" dewpoint temperature, °C (or surrogate)
R_s	daily solar radiation, MJ m ⁻² d ⁻¹
u_z	mean daily wind speed, m s ⁻¹ , at elevation z_w (can be measured over a short grass surface)

Required Data for hourly or shorter time steps:

T_{hr}	mean hourly air temperature, °C
T_{dew}	mean hourly dewpoint temperature, °C (or surrogate)
R_s	mean hourly solar radiation, MJ m ⁻² h ⁻¹
u_z	mean hourly wind speed, m s ⁻¹ , at elevation z_w (can be measured over a short grass surface)

Required Site Parameters:

z_w	elevation of wind speed measurement about ground surface, m
z_h	elevation of humidity and/or air temperature measurement above ground surface, m
z	elevation of site above mean sea level, m
Lat	latitude of site, degrees

For hourly computations, the user needs longitude of the weather site and the longitude of the center of the time zone.

Supporting Calculations for the ASCE and FAO Penman-Monteith Methods

The aerodynamic resistance for neutral stability conditions is:

$$r_a = \frac{\ln \left[\frac{z_w - d}{z_{om}} \right] \ln \left[\frac{z_h - d}{z_{oh}} \right]}{k^2 u_z} \quad (2)$$

where

r_a	aerodynamic resistance [$s m^{-1}$],
z_w	height of wind measurements [m],
z_h	height of humidity and or air temperature measurements [m],
d	zero plane displacement height [m], = 0.67 h
z_{om}	roughness length governing momentum transfer [m], = 0.123 h
z_{oh}	roughness length governing transfer of heat and vapor [m], = 0.0123 h
k	von Karman's constant, 0.41 [-],
u_z	wind speed at height z [$m s^{-1}$].
h	mean height of the vegetation, m

Note that in REF-ET, if the vegetation height of the measurement surface (weather station) is different from that of the reference vegetation, then d is computed using height of the weather station. See also equation 2-27 in Appendix 2 for adjusting wind speed to 2 m height.

Bulk surface resistance is:

$$r_s = \frac{r_l}{LAI_{active}} \quad (3)$$

where

r_s	(bulk) surface resistance [$s m^{-1}$],
r_l	bulk stomatal resistance of a well-illuminated leaf [$s m^{-1}$],
LAI_{active}	active (sunlit) leaf area index [$m^2 (leaf\ area)\ m^{-2} (soil\ surface)$].

Generally with reference crops that have full ground cover,

$$LAI_{active} = 0.5 LAI \quad (4)$$

For clipped grass:

$$LAI = 24 \text{ h} \quad (5)$$

where h is vegetation height, m

in REF-ET, $LAI = 23.8 \text{ h}$ is used so that r_s for 0.12 m grass calculates as $r_s = 70 \text{ s m}^{-1}$

For alfalfa:

$$\text{LAI} = 5.5 + 1.5 \ln(h) \quad (6)$$

Psychrometric and atmospheric parameters

Latent Heat of Vaporization (λ)³

$$\lambda = 2.501 - (2.361 \times 10^{-3}) T_{\text{mean}} \quad (7)$$

where: λ latent heat of vaporization [MJ kg^{-1}]
 T_{mean} mean air temperature for the time interval [°C]

The value of the latent heat varies only slightly over normal temperature ranges. For the FAO-56 Penman-Monteith (PM) and Standardized forms of the ASCE PM equation, a single value is taken: $\lambda = 2.45 \text{ MJ kg}^{-1}$.

For standardization, T_{mean} for 24-hour periods is defined as the mean of the daily maximum (T_{max}) and minimum temperatures (T_{min}) rather than as the average of hourly temperature measurements.

$$T_{\text{mean}} = \frac{T_{\text{max}} + T_{\text{min}}}{2} \quad (8)$$

Atmospheric Pressure (P)⁴

$$P = P_0 \left(\frac{T_{K0} - \alpha_l(z - z_0)}{T_{K0}} \right)^{\frac{g}{\alpha_l R}} \quad (9)$$

where: P atmospheric pressure at elevation z [kPa]
 P_0 atmospheric pressure at sea level = 101.3 [kPa]
 z elevation [m]
 z_0 elevation at reference level [m]
 g gravitational acceleration = 9.807 [m s⁻²]
 R specific gas constant = 287 [J kg⁻¹ K]
 α_l constant lapse rate moist air = 0.0065 [K m⁻¹]
 T_{K0} reference temperature [K] at elevation z_0 given by

$$T_{K0} = 273.16 + T_{\text{mean}} \quad (10)$$

where: T_{mean} is mean air temperature for the time period of calculation [°C]

³ Reference: Harrison (1963)

⁴ Reference: Burman *et al.* (1987)

When assuming $P_0 = 101.3$ [kPa] at $z_0 = 0$, and $T_{K0} = 293$ [K] for $T_{mean} = 20$ [$^{\circ}$ C], equation (8) becomes:

$$P = 101.3 \left(\frac{293 - 0.0065z}{293} \right)^{5.26} \quad (9b)$$

Atmospheric Density (ρ)⁵

$$\rho = \frac{1000 P}{T_{Kv} R} = 3.486 \frac{P}{T_{Kv}} \quad (11)$$

where: ρ atmospheric density [kg m^{-3}]
 R specific gas constant = 287 [$\text{J kg}^{-1} \text{K}^{-1}$]
 T_{Kv} mean virtual temperature for period [K]

$$T_{Kv} = T_K \left(1 - 0.378 \frac{e_a}{P} \right)^{-1} \quad (12)$$

where: T_K mean absolute temperature [K] : $T_K = 273.16 + T_{mean}$ [$^{\circ}$ C]
 e_a actual vapor pressure [kPa]

In derivation of the FAO-56 PM equation and the standardized ASCE (reduced form) PM equations, equation (12) is reduced to:

$$T_{Kv} \approx 1.01(T_{mean} + 273) \quad (\text{FAO-56 - 12})$$

T_{mean} is set equal to mean daily temperature for 24-hour calculation time steps.

Psychrometric Constant (γ)⁶

$$\gamma = \frac{c_p P}{\epsilon \lambda} = 0.00163 \frac{P}{\lambda} \quad (13)$$

where: γ psychrometric constant [$\text{kPa } ^{\circ}\text{C}^{-1}$]
 c_p specific heat of moist air = 1.013×10^{-3} [$\text{MJ kg}^{-1} ^{\circ}\text{C}^{-1}$]
 P atmospheric pressure [kPa]
 ϵ ratio molecular weight of water vapor/dry air = 0.622
 λ latent heat of vaporization [MJ kg^{-1}]

⁵ Reference: Smith *et al.* (1991)

⁶ Reference: Brunt (1952)

In the FAO-56 PM and ASCE-PM standardized (reduced form) equations, where λ is assumed to be constant, the equation for γ reduces to:

$$\gamma = 0.000665 P \quad (\text{FAO-56} - 13)$$

Slope of the Saturation Vapor Pressure Curve (Δ)⁷

$$\Delta = \frac{2504 \exp\left(\frac{17.27 T}{T + 237.2}\right)}{(T + 237.3)^2} \quad (14)$$

where: Δ slope vapor pressure curve [kPa $^{\circ}\text{C}^{-1}$]
 T air temperature [C]

In 24-hour calculations, Δ is calculated using mean daily air temperature. In hourly calculations T refers to the hourly mean, T_{hr} .

Saturation Vapor Pressure (e_s^0)⁸

The saturation vapor pressure function is:

$$e^0(T) = 0.6108 \exp\left(\frac{17.27 T}{T + 237.3}\right) \quad (15)$$

where: $e^0(T)$ saturation vapor pressure function [kPa]
 T air temperature [C]

Due to the non-linearity of the above equation, the mean saturation vapor pressure for a day, week, 10-day or month should be computed as the mean of the the saturation vapor pressure at the daily maximum air temperature and at the daily minimum air temperature for the period (this is done for the Kimberly Penman and all Penman-Monteith forms, including FAO-56 PM):

$$e_s = \frac{e^0(T_{\max}) + e^0(T_{\min})}{2} \quad (16)$$

For hourly time periods (or shorter), $e_s = e^0(T_{\text{hourly}})$.

For the 1963 Penman and the FAO-24 Penman, e_s for 24-hour or monthly time steps is computed as $e_s = e^0(T_{\text{mean}})$ where T_{mean} is the mean daily air temperature.

⁷ References: Tetens (1930), Murray (1967)

⁸ Reference: Tetens (1930)

Actual vapor pressure (e_a) derived from dewpoint temperature

The dewpoint temperature is the temperature to which the air needs to be cooled to make the air saturated. Therefore, the actual vapor pressure (e_a) is the saturation vapor pressure at the dewpoint temperature (T_{dew}) [°C], or:

$$e_a = e^o(T_{dew}) = 0.6108 \exp\left[\frac{17.27 T_{dew}}{T_{dew} + 237.3}\right] \quad (17)$$

Actual vapor pressure (e_a) derived from psychrometric data

The actual vapor pressure can be determined from the difference between the dry and wet bulb temperatures (the wet bulb depression):

$$e_a = e^o(T_{wet}) - \gamma_{psy} (T_{dry} - T_{wet}) \quad (18)$$

where e_a actual vapor pressure [kPa],
 $e^o(T_{wet})$ saturation vapor pressure at wet bulb temperature [kPa],
 γ_{psy} psychrometric constant of the instrument [$\text{kPa } ^\circ\text{C}^{-1}$],
 $T_{dry} - T_{wet}$ wet bulb depression, with T_{dry} the dry bulb and T_{wet} the wet bulb temperature [°C].

The psychrometric constant of the instrument is given by:

$$\gamma_{psy} = a_{psy} P \quad (19)$$

where a_{psy} is a coefficient depending on the type of ventilation of the wet bulb [$^\circ\text{C}^{-1}$], and P is the atmospheric pressure [kPa]. The coefficient a_{psy} depends mainly on the design of the psychrometer and rate of ventilation around the wet bulb. The following values are recommended in FAO-56:

$a_{psy} = 0.000662$	for ventilated (Asmann type) psychrometers, with an air movement of some 5 m/s,
0.000800	for natural ventilated psychrometers (about 1 m s ⁻¹),
0.001200	for non-ventilated psychrometers installed indoors.

In REF-ET, however, a_{psy} is computed as: $a_{psy} = 0.000661 P (1 + 0.00115 T_{wet})$ following ASCE Manual 70, where P is mean atmospheric pressure in kPa and T_{wet} is in °C.

Actual vapor pressure (e_a) derived from relative humidity data

The actual vapor pressure can also be calculated from the relative humidity. Depending on the availability of the humidity data, different equations should be used.

- **From RH_{max} and RH_{min}:**

$$e_a = \frac{e^o(T_{min}) \frac{RH_{max}}{100} + e^o(T_{max}) \frac{RH_{min}}{100}}{2} \quad (20)$$

where e_a actual vapor pressure [kPa],

$e^o(T_{min})$	saturation vapor pressure at daily minimum temperature [kPa],
$e^o(T_{max})$	saturation vapor pressure at daily maximum temperature [kPa],
RH_{max}	maximum relative humidity [%],
RH_{min}	minimum relative humidity [%].

For periods of a week, ten days or a month, RH_{max} and RH_{min} are generally obtained by dividing the sum of the daily values by the number of days in that period.

- **From RH_{max} :**

When using equipment where errors in estimating RH_{min} may be large, or when RH data integrity are in doubt, then one may elect to use only RH_{max} :

$$e_a = e^o(T_{min}) \frac{RH_{max}}{100} \quad (21a)$$

- **From RH_{min} :**

Sometimes, estimates of daily RH_{min} are available and must be used to predict e_a . However, these estimates are less desirable than other approaches:

$$e_a = e^o(T_{max}) \frac{RH_{min}}{100} \quad (21b)$$

- **From RH_{mean} :**

In the absence of RH_{max} and RH_{min} :

$$e_a = \frac{RH_{mean}}{100} \left[\frac{e^o(T_{max}) + e^o(T_{min})}{2} \right] \quad (22)$$

where RH_{mean} is the mean relative humidity, defined as the average between RH_{max} and RH_{min} . However, Equation 22 is less desirable than are Equations 20 or 21.

- **For Hourly or Shorter Periods:**

For hourly or shorter periods, RH can be assumed to be relatively constant across the time step so that:

$$e_a = \frac{RH_{hr}}{100} e^o(T_{hr}) \quad (23)$$

where RH_{hr} and T_{hr} are the the mean relative humidity and air temperature for the hourly or shorter period, % and °C.

Net radiation (R_n)

The net radiation (R_n) is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \quad (24)$$

Net solar or net shortwave radiation (R_{ns})

Net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - \alpha) R_s \quad (25)$$

where R_{ns} net solar or shortwave radiation [$\text{MJ m}^{-2} \text{d}^{-1}$] or [$\text{MJ m}^{-2} \text{h}^{-1}$],
 α albedo or canopy reflection coefficient, which is assumed to be 0.23 for the hypothetical grass and alfalfa reference crops used in the FAO-56 and ASCE PM equations [dimensionless],
 R_s the incoming solar radiation [$\text{MJ m}^{-2} \text{d}^{-1}$] or [$\text{MJ m}^{-2} \text{h}^{-1}$].

For the 1982 Kimberly Penman, R_n is computed according to Wright (1982) using a variable albedo computed using Eqn. 46. The Wright (1982) procedure uses other variable coefficients for other terms also.

Net longwave radiation (R_{nl})

$$R_{nl} = \sigma \left[\frac{T_{\max,K}^4 + T_{\min,K}^4}{2} \right] (0.34 - 0.14 \sqrt{e_a}) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \quad (26)$$

The following calculation for 24-hour net longwave radiation is that used in FAO-56:

where R_{nl} net outgoing longwave radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
 σ Stefan-Boltzmann constant [$4.903 \cdot 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ d}^{-1}$],
 $T_{\max,K}$ maximum absolute temperature during the 24-hour period [$K = {}^\circ\text{C} + 273.16$],
 $T_{\min,K}$ minimum absolute temperature during the 24-hour period [$K = {}^\circ\text{C} + 273.16$],
 e_a actual vapor pressure [kPa],
 R_s/R_{so} relative shortwave radiation (limited to ≤ 1.0),
 R_s measured or calculated solar radiation [$\text{MJ m}^{-2} \text{d}^{-1}$],
 R_{so} calculated clear-sky radiation [$\text{MJ m}^{-2} \text{d}^{-1}$].

The FAO-24 Penman equation (Doorenbos and Pruitt, 1977) uses $T_{\text{mean},K}$ in the place of $T_{\max,K}$ and $T_{\min,K}$. In addition, the value "0.34" in Eq. 26 equals "0.3xx" in the FAO-24 Penman method.

It is important to limit the ratio of R_s/R_{so} in equations 26 and 27 to $0.2 < R_s/R_{so} < 1.0$. Ratios greater than 1.0 will cause errors in estimated long wave emission from the atmosphere. Ratios less than 0.2 are generally not possible even on very cloudy days and may indicate a problem in the R_s data.

For hourly or shorter periods:

$$R_{nl} = \sigma T_{hr,K}^4 \left(0.34 - 0.14 \sqrt{e_a} \right) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \quad (27)$$

where R_{nl} net outgoing longwave radiation [$\text{MJ m}^{-2} \text{ h}^{-1}$],
 σ Stefan-Boltzmann constant [$2.043 \cdot 10^{-10} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ h}^{-1}$],
 $T_{hr,K}$ mean absolute temperature during the hourly period [$K = {}^\circ\text{C} + 273.16$],
 e_a actual vapor pressure [kPa],
 R_s/R_{so} relative shortwave radiation (limited to ≤ 1.0), (see discussion under R_{so})
 R_s measured or calculated solar radiation [$\text{MJ m}^{-2} \text{ h}^{-1}$],
 R_{so} calculated clear-sky radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$].

Soil Heat Flux Density (G)

- **For daily and ten-day periods:**

The magnitude of the daily or ten-day soil heat flux beneath a fully vegetated grass or alfalfa reference surface is relatively small. Therefore, it is ignored and thus:

$$G_{day} \approx 0 \quad (28)$$

- **For monthly periods:**

On monthly timesteps, seasonal warming of soil can be significant. Assuming a constant soil heat capacity of about $2.0 \text{ MJ m}^{-3} {}^\circ\text{C}^{-1}$ and an appropriate soil depth, G for monthly periods is estimated in ASCE Manual 70 and in FAO-56 as:

$$G_{month,i} = 0.07 (T_{month,i+1} - T_{month,i-1}) \quad (29)$$

However, in REF-ET, since the $T_{month,i+1}$ is unknown when the previous line of data are being evaluated, *the following equation from FAO-56 is used in REF-ET:*

$$G_{month,i} = 0.14 (T_{month,i} - T_{month,i-1}) \quad (30)$$

where $T_{month,i}$ mean air temperature of month i [${}^\circ\text{C}$],
 $T_{month,i-1}$ mean air temperature of previous month [${}^\circ\text{C}$],
 $T_{month,i+1}$ mean air temperature of next month [${}^\circ\text{C}$].

- **For hourly or shorter periods:**

For hourly (or shorter) calculations, G beneath a dense cover of grass or alfalfa does not correlate well with air temperature. Hourly G can be approximated during daylight periods as:

$$G_{hr} = K_G \exp(-0.5 LAI) R_n \quad (31)$$

where

$$K_G = 0.4 \text{ during daytime } (R_n > 0)$$

$$K_G = 1.6-2.0 \text{ during nighttime } (R_n < 0)$$

For clipped grass, equation 31 becomes (equations 32 and 33)

$$G_{\text{hr daytime}} = 0.1 R_n \quad (32\text{grass})$$

$$G_{\text{hr nighttime}} = 0.5 R_n \quad (33\text{grass})$$

For alfalfa, equation 31 becomes

$$G_{\text{hr daytime}} = 0.04 R_n \quad (32\text{alfalfa})$$

$$G_{\text{hr nighttime}} = 0.2 R_n \quad (33\text{alfalfa})$$

Where the soil is warming, the soil heat flux G is positive. The amount of energy required for this process is subtracted from R_n when estimating evapotranspiration.

Clear-sky solar radiation (R_{so})

- For near sea level:

$$R_{\text{so}} = 0.75 R_a \quad (34)$$

where R_{so} clear-sky solar radiation [$\text{MJ m}^{-2} \text{d}^{-1}$] or [$\text{MJ m}^{-2} \text{h}^{-1}$],
 R_a extraterrestrial radiation [$\text{MJ m}^{-2} \text{d}^{-1}$] or [$\text{MJ m}^{-2} \text{h}^{-1}$]

- When calibrated values for a_s and b_s are not available at elevations above 300 m:

$$R_{\text{so}} = (0.75 + 2 (10^{-5}) z) R_a \quad (35)$$

where z station elevation above sea level [m].

This equation is referred to in REF-ET as the FAO-56a method for R_{so} . This equation is used for all 24-hour timestep calculations in REF-ET. Other more complex estimates for R_{so} , which include turbidity and water vapor effects, are discussed in Appendix 2. These more complex forms, including the form term FAO-56c, are used for hourly computations of R_{so} in REF-ET. These more complex forms can be used for assessing integrity of solar radiation data. When trusted R_s data are available that have been cross-calibrated or verified using an internationally traceable standard, plots of R_s vs. time can be used to calibrate Equation 34, 35 or the more complex R_{so} forms in Appendix 2 for local conditions. For example, very high humidity in the midwest can create a slight haze that may reduce R_{so} (and measurements of R_s) by as much as 10% from ideal R_{so} during midsummer .

R_s/R_{so} for Hourly Periods

Since the ratio R_s/R_{so} is used in the calculation of net radiation to represent cloud cover, when calculating R_{nl} for hourly periods during the night time (when there is no R_s), it is necessary to set the ratio R_s/R_{so} equal to the R_s/R_{so} calculated for a time period occurring 2-3 hours before sunset, before the sun angle becomes small. This will generally serve as a good approximation of cloudiness occurring during the subsequent night time period. The hourly period that is 2 to 3 hours before sunset can be identified during computation of R_a as the period where the solar time angle ω is within the range $(\omega_s - 0.79) \leq \omega \leq (\omega_s - 0.52)$, where ω and sunset hour angle ω_s are calculated in an appendix. This is the method that is used in REF-ET. Limits placed on R_s/R_{so} in REF-ET are $0.2 < R_s/R_{\text{so}} < 1.0$. Where information on ω before sunset is missing, i.e., for the first day of hourly calculations, the ratio of $R_s/R_{\text{so}} = 0.7$ may be assumed during the first night.

The Standardized ASCE Penman-Monteith Equation(s)

In 1999 and 2000, the ASCE Technical Committee on Evapotranspiration in Irrigation and Hydrology recommended that two Standardized Reference Evapotranspiration Equations be adopted for general practice along with *standardized* computational procedures. The standardized equations are derived from the ASCE Penman-Monteith (ASCE-PM) equation (Eq. 1-6 of this appendix) as described in ASCE Manual 70 (Jensen et al., 1990), in the ICID Bulletin (Allen et al., 1994), and in the ASCE Hydrology Handbook (1996). The computation of parameters for the reference equations incorporates procedures for calculating net radiation, soil heat flux, vapor pressure deficit, and air density as described in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998). A constant latent heat of vaporization, λ , equal to 2.45 MJ kg^{-1} is used for simplicity. Albedo for the reference surfaces is fixed at a constant 0.23. The equations assume that measurement heights for air temperature and water vapor content are made at a height in the range of 1.5 to 2.5 m above the ground. The standardized equations require that wind speed, u_2 , is measured at or is adjusted to a 2 m measurement height. The coefficients in the ASCE standardized reference evapotranspiration equations presume that the weather data are measured over a grassed weather station having a vegetation height of about 0.1 to 0.2 m.

The two standardized reference evapotranspiration (ET) definitions by ASCE (2000) are:

Standardized Reference Evapotranspiration Equation, Short (ET_o): Reference ET for a *short* crop having an approximate height of 0.12 m (similar to grass).

Standardized Reference Evapotranspiration Equation, Tall (ET_r): Reference ET for a *tall* crop having an approximate height of 0.50 m (similar to alfalfa).

Both standardized reference equations were derived from the ASCE-PM equation (Eq. 1) by fixing $h = 0.12 \text{ m}$ for the short crop (ET_o) and $h = 0.50 \text{ m}$ for the tall crop (ET_r). The short crop and tall crop reference equations are traceable to the commonly used terms grass reference and alfalfa reference.

As a part of the standardization, the “full” form of the Penman-Monteith equation and associated equations for calculating aerodynamic and bulk surface resistance have been combined and reduced into a single equation having two constants in the same manner as done for the FAO-PM equation (Smith et al., 1991; Allen et al., 1998). The constants vary as a function of the reference surface (ET_o or ET_r) and time step (hourly or daily). This was done to simplify the presentation and application of the methods. The constant in the right-hand side of the numerator (C_n) is a function of the time step and aerodynamic resistance (i.e., reference type). The constant in the denominator (C_d) is a function of the time step, bulk surface resistance, and aerodynamic resistance (the latter two terms vary with reference type, time step and daytime/nighttime). The C_d constants reflect surface resistance values that are 70, 50, and 200 s m^{-1} for ET_o for 24-hour, hourly daytime, and hourly nighttime periods and that are 45, 30, and 200 s m^{-1} for ET_r for 24-hour, hourly daytime, and hourly nighttime periods.

Equation 36 presents the form of the Standardized ASCE Reference Evapotranspiration Equation for all hourly and daily calculation time steps. Table A-1 provides values for the constants C_n and C_d .

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1+C_d u_2)} \quad (36)$$

where	ET_{ref}	Short (ET_O) or tall (ET_r) reference crop evapotranspiration [mm day^{-1} for daily time steps or mm hour^{-1} for hourly time steps],
	R_n	net radiation at the crop surface [$\text{MJ m}^{-2} \text{ day}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{ hour}^{-1}$ for hourly time steps],
	G	soil heat flux density at the soil surface [$\text{MJ m}^{-2} \text{ day}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{ hour}^{-1}$ for hourly time steps],
	T	mean daily or hourly air temperature at 1.5 to 2.5-m height [$^{\circ}\text{C}$],
	u_2	mean daily or hourly wind speed at 2-m height [m s^{-1}],
	e_s	mean saturation vapor pressure at 1.5 to 2.5-m height [kPa]; for daily computation, value is the average of e_s at maximum and minimum air temperature,
	e_a	mean actual vapor pressure at 1.5 to 2.5-m height [kPa],
	Δ	slope of the vapor pressure-temperature curve [kPa $^{\circ}\text{C}^{-1}$],
	γ	psychrometric constant [kPa $^{\circ}\text{C}^{-1}$],
	C_n	numerator constant for reference type and calculation time step, and
	C_d	denominator constant for reference type and calculation time step.

Table A-1. Values for C_n and C_d in Equation 36

<i>Calculation Time Step</i>	<i>Short Reference, ET_O</i>		<i>Tall Reference, ET_r</i>		<i>Units for ET_O, ET_r</i>	<i>Units for R_n, G</i>
	C_n	C_d	C_n	C_d		
Daily or monthly	900	0.34	1600	0.38	mm d^{-1}	$\text{MJ m}^{-2} \text{ d}^{-1}$
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	$\text{MJ m}^{-2} \text{ h}^{-1}$
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	$\text{MJ m}^{-2} \text{ h}^{-1}$

Equation 36 with C_n and C_d for daily time steps is exactly the same as the FAO-PM equation (Eq. 37). However, for hourly timesteps, the standardized ASCE PM for ET_O uses a smaller value for r_s during daytime and a larger value for r_s during nighttime than does the FAO-PM equation.

The FAO-56 Penman-Monteith Equation

The FAO-56 Penman-Monteith equation is a grass reference equation that was derived from the ASCE equations (1 – 6) previously listed by fixing $h = 0.12$ m for clipped grass and by assuming measurement heights of $z_w = 2$ m and $z_h = 2$ m and using $\lambda = 2.45$ MJ kg $^{-1}$. The result is an equation that defines the reference evapotranspiration from a hypothetical grass surface having a fixed height of 0.12 m, bulk surface resistance of 70 s m $^{-1}$, and albedo of 0.23. For 24-hour time steps:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (37)$$

where

ET_o	grass reference evapotranspiration [mm day $^{-1}$],
R_n	net radiation at the crop surface [MJ m $^{-2}$ day $^{-1}$],
G	soil heat flux density [MJ m $^{-2}$ day $^{-1}$],
T	mean daily air temperature at 2 m height [$^{\circ}$ C],
u_2	wind speed at 2 m height [m s $^{-1}$],
e_s	saturation vapor pressure [kPa],
e_a	actual vapor pressure [kPa],
$e_s - e_a$	saturation vapor pressure deficit [kPa],
Δ	slope vapor pressure curve [kPa $^{\circ}$ C $^{-1}$],
γ	psychrometric constant [kPa $^{\circ}$ C $^{-1}$].

The FAO-56 Penman-Monteith equation for hourly time steps (assuming that $r_s = 70$ s m $^{-1}$) is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T_{hr} + 273} u_2 (e^o(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (38)$$

where

ET_o	grass reference evapotranspiration [mm h $^{-1}$],
R_n	net radiation at the crop surface [MJ m $^{-2}$ h $^{-1}$],
G	soil heat flux density [MJ m $^{-2}$ h $^{-1}$],
T	mean daily air temperature at 2 m height [$^{\circ}$ C],
u_2	wind speed at 2 m height [m s $^{-1}$],
e_s	saturation vapor pressure [kPa],
e_a	actual vapor pressure [kPa],
$e_s - e_a$	saturation vapor pressure deficit [kPa],
Δ	slope vapor pressure curve [kPa $^{\circ}$ C $^{-1}$],
γ	psychrometric constant [kPa $^{\circ}$ C $^{-1}$].

Precautions when Comparing the FAO-56 and Standardized ASCE Penman-Monteith Equations to Measured Values

The simplified form of the Penman-Monteith equation used in FAO-56 and in ASCE Standardized PM equations presumes a fixed vegetation height of 0.12m for grass or 0.50m for alfalfa, along with the associated surface resistances as defined by ASCE. It is important that when the ET_o or ET_r calculations are to be compared against field measurements of "reference" ET, that the full ASCE form of the Penman-Monteith method be used, with height h varied to match field observations. In addition, the above forms of the Penman-Monteith equation, including the ASCE forms, presume that the soil water content is adequate to support full evapotranspiration and that the soil and vegetation are wetted on a frequency of about once per five days during summer for grass (including irrigation and rainfall) and about once per 10 days during summer for alfalfa. More frequent wetting of the vegetation and soil can be expected to increase the measured ET by up to 10%.

The Penman Equation

The classical form of the Penman equation (Penman, 1948) is:

$$ET_o \quad \text{or} \quad ET_r = \left(\frac{\Delta}{\Delta + \gamma} (R_n - G) + K_w \frac{\gamma}{\Delta + \gamma} (a_w + b_w u_2) (e_s - e_a) \right) / \lambda \quad (39)$$

where:
 K_w is a units constant
 a_w and b_w are wind function coefficients
 u_2 wind speed at 2 m, [$m s^{-1}$]
 λ latent heat of vaporization, $MJ kg^{-1}$

All other terms and definitions are the same as those used for the Penman-Monteith equation. Parameter $K_w = 6.43$ for ET_o in $mm d^{-1}$ and $K_w = 0.268$ for ET_o in $mm hour^{-1}$. The a_w and b_w terms are empirical wind coefficients that have often received local or regional calibration. The values for a_w and b_w for the original Penman equation (Penman, 1948 and Penman, 1963) were 1.0 and 0.537, respectively, for wind speed in $m s^{-1}$, $e_s - e_a$ in kPa and grass ET_o in $mm d^{-1}$.

The Kimberly Penman Method

The 1982 and 1996 Kimberly Penman methods (Wright, 1982) use the original form of the Penman equation along with wind coefficients that vary with time of year. In addition, the coefficients used for computation of net radiation and the method to predict 24-hour soil heat flux varies from the procedures given in the main body.

The 1982 Kimberly-Penman equation was developed from intensive studies of evapotranspiration using measurements of full-cover alfalfa ET from precision weighing lysimeters at Kimberly, Idaho (Wright and Jensen 1972; Wright 1981; Wright 1982; Wright 1988). The 1996 Kimberly wind function for grass ET_o (Wright, 1996) was developed from five years of weighing lysimeter data from clipped fescue grass having high leaf area and maintained at 0.8 to 0.15 m height and well-fertilized.

The Kimberly Penman and associated wind functions are intended for application with 24-hour time steps ($K_w = 2.62$). The form and all units and definitions are the same as those in Eq. 39. The Kimberly a_w and b_w wind function coefficients for alfalfa vary with time of year and are computed for ET_r as (Wright 1987, pers. comm. and Jensen et al. 1990):

$$a_w = 0.4 + 1.4 \exp\left(-\left(\frac{J-173}{58}\right)^2\right) \quad (40r)$$

$$b_w = 0.605 + 0.345 \exp\left(-\left(\frac{J-243}{80}\right)^2\right) \quad (41r)$$

where J is the day of the year. For latitudes south of the equator, one should use J' in place of J , where $J' = (J - 182)$ for $J \geq 182$ and $J' = (J + 182)$ for $J < 182$. The $(e_s - e_a)$ term in the 1982 and 1996 Kimberly Penmans is computed the same as for the Penman-Monteith equation (as the average of e_s computed at maximum and minimum temperatures). Analyses by Jensen et al. (1990) found the 1982 Kimberly Penman, although developed for a 42° latitude and semiarid climate, to predict well in other latitudes and regions.

The Kimberly a_w and b_w wind function coefficients for grass vary with time of year and are computed for ET_o as (Wright 1996):

$$a_w = 0.3 + 0.58 \exp\left(-\left(\frac{J-170}{45}\right)^2\right) \quad (40o)$$

$$b_w = 0.32 + 0.54 \exp\left(-\left(\frac{J-228}{67}\right)^2\right) \quad (41o)$$

In the "1972" Kimberly Penman method (Wright and Jensen, 1972), fixed values were used for a_w and b_w . These values were $a_w = 0.75$ and $b_w = 0.993$. The 1972 Kimberly Penman is no longer recommended by Wright (1999, personal communication).

In the original (Wright, 1982) definition for the 1982 Kimberly Penman equation, net outgoing long wave radiation was computed for Kimberly as:

$$R_{nl} = \sigma \left[\frac{T_{max,K}^4 + T_{min,K}^4}{2} \right] \left(a_1 + b_1 \sqrt{e_a} \right) \left(a_c \frac{R_s}{R_{so}} + b_c \right) \quad (42)$$

where	R_{nl}	net outgoing longwave radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$],
	σ	Stefan-Boltzmann constant [$4.903 \cdot 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ d}^{-1}$],
	$T_{max,K}$	maximum absolute temperature during the 24-hour period [$K = {}^\circ\text{C} + 273.16$],
	$T_{min,K}$	minimum absolute temperature during the 24-hour period [$K = {}^\circ\text{C} + 273.16$],
	e_a	actual vapor pressure [kPa],
	R_s/R_{so}	relative shortwave radiation (limited to ≤ 1.0),
	R_s	measured or calculated solar radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$],
	R_{so}	calculated clear-sky radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$].

a_1 for alfalfa at Kimberly (42° N) is:

$$a_1 = 0.26 + 0.1 \exp(-[0.0154(J - 180)]^2) \quad (43)$$

where J is the day of the year, and where J is replaced with J' as described for Eq. 40 and 41 for the southern hemisphere. $b_1 = -0.139$ in Wright (1982).

Wright (1982) predicted a_c and b_c as:

$$\begin{aligned} a_c &= 1.126 \text{ and } b_c = -0.07 \quad \text{for } R_s / R_{so} > 0.7 \\ a_c &= 1.017 \text{ and } b_c = -0.06 \quad \text{for } R_s / R_{so} \leq 0.7 \end{aligned} \quad (44)$$

Wright (1982) predicted albedo as:

$$\alpha = 0.29 + 0.06 \sin[(J + 96) / 57.3] \quad (45)$$

where J is the day of the year, and where J is replaced with J' as described for Eq. 40 and 41 for the southern hemisphere.

Soil heat flux for 24-hour periods was predicted for the alfalfa reference by Wright (1982) using the difference between mean air temperature of the current day and the mean air temperature of the previous three days:

$$G_{24} = 0.38 \left(T_{\text{mean}} - \sum_{i=1}^3 T_{\text{mean } i} / 3 \right) \quad (46)$$

where G_{24} is 24-hour soil heat flux by Wright (1982) in $\text{MJ m}^2 \text{ d}^{-1}$, T_{mean} is mean air temperature on the current day and $T_{\text{mean } i}$ is the mean air temperatures for the previous three days. Equation 46 may not predict well under various conditions. In a study on 24-hour heat flux at Kimberly and Logan, Allen and Wright (unpublished paper, 1996) found that using $G=0$ for 24-hour periods under alfalfa and grass produced less error relative to measured G than using Eq. 46.

The CIMIS Penman Method

Pruitt (Pruitt and Doorenbos 1977a; Pruitt et al. 1984) developed a_w and b_w for predicting grass ET_o for hourly periods for a clipped grass reference. These coefficients have been adopted for standard ET_o estimation in the California Irrigation Management Information Service (CIMIS) (Snyder and Pruitt, 1992). The result is the "CIMIS" Penman ET_o equation where $a_w = 0.29$ and $b_w = 0.53$ for $R_n > 0$ and $a_w = 1.14$ and $b_w = 0.40$ for $R_n \neq 0$. These coefficients are applied hourly using Eq. 39 where $ET_o = \text{mm hour}^{-1}$, $R_n = \text{MJ m}^{-2} \text{ hour}^{-1}$, and $K_w = 0.268$.

The net radiation calculation for the CIMIS method is different than that described in Appendix 1 (FAO-56 approach) and from that described by Wright (1982) above. In REF-ET, R_n for the CIMIS Penman equation is computed using the FAO-56 procedure and coefficients, due to problems in the prediction of R_s/R_{so} and R_{nl} by CIMIS routines when R_s/R_{so} is close to 1.0. Standard CIMIS calculations assume $G = 0$, although G in hourly applications should normally be considered. However, in REF-ET, G is set equal to $G = 0$ to be consistent with standard CIMIS usage.

Other Penman Methods

The Penman (1948) equation is the same as the Penman (1963). The only difference is that the 1948 publication suggested estimating R_n as a function of percent sunshine hours rather than on

solar radiation, due to the technology at the time. For the Penman (1948, 1963) equation, $a_w = 1.0$ and $b_w = 0.536$.

The FAO-24 Penman is applied in REF-ET using net radiation as computed in the FAO-24 publication. In the FAO-24 Penman, $a_w = 1.0$ and $b_w = 0.862$ for u_2 in $m\ s^{-1}$ and vapor pressure in kPa and radiation in $MJ\ m^{-2}\ d^{-1}$. The FAO-24 “correction” is applied using the regression equation by Allen and Pruitt (1991).

The FAO-24 Radiation, Blaney-Criddle, and Pan evaporation equations are applied as instructed by FAO-24, except that the correction factors are calculated using regression equations by Allen and Pruitt (1991) rather than using the FAO-24 tables or graphs.

Hourly vs. 24-hour Computation Time Steps

Many automated agricultural weather stations collect and present weather measurements for hourly or shorter time steps. Many other weather systems provide only 24-hour summaries. In some climates where diurnal (within on day) changes in wind speed, cloudiness, or air temperatures are substantially different from general conditions, using hourly timesteps may improve the total 24-hour estimate.

When hourly weather measurements are available, they can be applied with the Penman-Monteith equations or CIMIS Penman equation. The ASCE Technical Committee on Standardization of Reference ET Calculations undertook and intensive study of hourly and daily calculations of ET_o and ET_r during 1999 for agricultural weather stations across the U.S. Their study found that when the ASCE-PM equation is applied with hourly data, that values for surface resistance should be reduced during daytime hours in order for hourly calculations of ET to sum to 24-hour values that are similar to daily time-step applications. Surface resistances at nighttime were set at $200\ s\ m^{-1}$ to reflect stomatal closure with a moist underlying soil surface. Values suggested for r_s for hourly and 24-hour timesteps are as defined earlier in this appendix. Other applications of the Penman-Monteith method for grass have increased the nighttime surface resistance (r_s) also (i.e., $r_s = 200\ s\ m^{-1}$ is used by Campbell Scientific, Inc., 1993, for nighttime periods). In hourly applications with the PM equations, soil heat flux density is computed using $G = 0.1\ R_n$ during daytime and $G = 0.5\ R_n$ during nighttime.

The FAO-Penman-Monteith equation is applied with a fixed $r_s = 70\ s\ m^{-1}$ for ET_o regardless of time step. In many climates, this method produces hourly calculations of ET_o that are similar to those obtained when the equation is applied on a 24-hour basis. However, under some climatic conditions, the summed hourly ET_o may underpredict daily ET. Close agreement between hourly and 24-hour computation timesteps have been found with the FAO-Penman-Monteith equation in California, Utah, Idaho, Colorado, and Ohio climates (ASAE monograph (in prep.) and ASCE Hydrology Handbook (Allen et al., 1996)).

The second “full” ASCE PM equation in the REF-ET list of equations (Table 1) allows the user to enter different values for r_s for 24-hour and hourly daytime and hourly nighttime time steps. These values are then modified inside REF-ET if the height of the reference changes with time as indicated in each data line of the data file. The modification is according to LAI as computed for each reference type as described earlier.

Utilization of hourly data and hourly computation time steps does present additional challenges and concerns. These include data integrity assessment. Data integrity assessment (of temperature, solar radiation, wind and humidity data) can become somewhat more complicated for hourly data (see Allen, 1996 ASCE article on integrity assessment) and estimation of missing data can become less certain. In addition, uncertainty in predicting net radiation, soil heat flux, and surface resistance

during nighttime increases. In situations where data are missing, it is sometimes difficult to “borrow” data from nearby stations due to time biases in the data.

Hourly computations do permit the application of stability correction functions in Eq. 1 and 2, as illustrated in the current ASCE Hydrology Handbook (Allen et al., 1996). However, these functions are relatively complicated to apply, and their application argues for the additional application of surface resistance (or surface conductance) functions that vary with air temperature, vapor pressure and solar radiation (see the ASCE Hydrology Handbook for examples). However, these functions, although they may improve accuracy of predicting for a specific vegetative surface, have not been included in the standardized procedures for the ASCE or FAO Penman-Monteith equations for the sake of simplicity and consistency and general lack of required profile measurement data. In addition stability corrections require measurements of air temperature at several heights or measurements of surface temperature. Fortunately, the lower boundary layer over well-watered reference surfaces of grass and alfalfa are generally near neutral buoyancy and stability since $ET \sim R_n - G$ and therefore sensible heat flux, $H, \sim 0$. Therefore, the stability correction for reference crops is generally quite small. Application of stability and conductance functions are not considered to be a part of standard practice for reference ET prediction. These functions **are not** included in REF-ET.

The 1985 Hargreaves Method

The 1985 Hargreaves method requires only maximum and minimum daily air temperature and it can be applied on 24-hour, weekly, 10-day, or monthly time steps. It has the form:

$$ET_o = 0.0023(T_{\max} - T_{\min})^{0.5} (T_{\text{mean}} + 17.8) R_a \quad (47)$$

where:

ET_o	grass reference ET, mm d ⁻¹
T_{\max}	maximum daily air temperature, °C
T_{\min}	minimum daily air temperature, °C
T_{mean}	mean daily air temperature, computed as $(T_{\max} + T_{\min}) / 2$
R_a	extraterrestrial radiation, mm d ⁻¹ (see appendix 1)

$$R_a \text{ in mm d}^{-1} = R_a \text{ in MJ m}^{-2} \text{ d}^{-1} / 2.45.$$

The Hargreaves method is a useful ET_o method to include in reference ET calculations, even when applying the Penman or Penman-Monteith equation, since this simple equation is useful for 1) making quick estimates using only a table of extraterrestrial radiation, and 2) as a computational check on other more complicated computations of ET_o . The Penman, Penman-Monteith, and Hargreaves methods should match within 15% over a 5 day or longer period, unless unusual wind speed or diurnal patterns are present.

The Makkink, Turc and Priestley-Taylor Methods

The Makkink, Turc, and Priestley-Taylor methods are radiation and temperature based methods for ET_o . The first two methods were developed in the Netherlands and the latter in Australia. The Makkink (1957) method is commonly used in western Europe:

$$ET_o = 0.61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{2.45} - 0.12 \quad (48)$$

where ET_o is in mm d^{-1} , R_s is solar radiation in $\text{MJ m}^{-2} \text{d}^{-1}$, and Δ and γ are as defined for the Penman equations [$\text{kPa } ^\circ\text{C}^{-1}$]. Constant 2.45 is latent heat of vaporization at approximately 20°C .

The Turc (1961) equation has the form:

$$ET_o = a_T 0.013 \frac{T_{\text{mean}}}{T_{\text{mean}} + 15} \frac{23.8856 R_s + 50}{\lambda} \quad (49)$$

where ET_o is in mm d^{-1} , R_s is solar radiation in $\text{MJ m}^{-2} \text{d}^{-1}$, T_{mean} is mean daily air temperature in $^\circ\text{C}$, and λ is latent heat of vaporization in MJ kg^{-1} . The Turc equation should only be applied if $T_{\text{mean}} > -10^\circ\text{C}$. The coefficient a_T is defined as $a_T = 1.0$ for $RH_{\text{mean}} \geq 50\%$, where RH_{mean} is mean daily relative humidity. When $RH_{\text{mean}} < 50\%$, then $a_T = 1 + (50-RH_{\text{mean}})/70$ where RH_{mean} is in %.

The Priestley-Taylor (1972) equation has the form:

$$ET_o = 1.26 \frac{\Delta}{\Delta + \gamma} \frac{R_n - G}{\lambda} \quad (50)$$

where ET_o is in mm d^{-1} , R_n is net radiation and G is soil heat flux density in $\text{MJ m}^{-2} \text{d}^{-1}$, λ is latent heat of vaporization in MJ kg^{-1} and Δ and γ are as defined for the Penman equations [$\text{kPa } ^\circ\text{C}^{-1}$].

Appendix 2

Additional Supporting Equations

Dew Point Temperature (T_{dew})

When it is not observed, T_{dew} can be computed from e_a by inverting the Tetens equation:

$$T_{dew} = \frac{116.91 + 237.3 \ln(e_a)}{16.78 - \ln(e_a)} \quad (2-1)$$

where: T_{dew} dew point temperature [$^{\circ}\text{C}$]
 e_a actual vapor pressure [kPa]

For the case of measurements with the Assmann psychrometer, T_{dew} can be calculated from⁹

$$T_{dew} = (112 + 0.9 T_{wet}) \left(\frac{e_a}{e^o(T_{wet})} \right)^{1/8} - 112 + 0.1 T_{wet} \quad (2-2)$$

Equation 2-2 is not used in REF-ET. Instead, T_{dew} is computed from wet and dry bulb temperatures by first computing e_a using Eq. 18 of Appendix 1 and then using Eq. 2-1.

Short Wave Radiation on a Clear-Sky Day (R_{so})¹⁰

The calculation of R_{so} is required for computing net long wave radiation and for checking calibration of pyranometers and integrity of R_{so} data. Besides equations 34 and 35, (equation (35) is valid for station elevations less than 6000 m having low air turbidity), for areas of high turbidity caused by pollution or airborne dust or for regions where the sun angle is significantly less than 50° so that the path length of radiation through the atmosphere is increased, an adaption of Beer's law can be employed where P is used to represent atmospheric mass:

$$R_{so} = R_a \exp\left(\frac{-0.0021 P}{K_t \sin \phi}\right) \quad (2-3)$$

where: K_t turbidity coefficient [], $0 < K_t \leq 1.0$ where $K_t = 1.0$ for clean air and $K_t \sim 0.5$ for extremely turbid, dusty or polluted air.
 P atmospheric pressure [kPa]
 ϕ angle of the sun above the horizon [rad]
 R_a extraterrestrial radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$] or [$\text{MJ m}^{-2} \text{ h}^{-1}$]

⁹ Reference: Bosen (1958); Jensen *et al.* (1990)

¹⁰ Reference: Allen (1996)

The turbidity parameter K_t in Equations 2-3 and 2-7 can be adjusted downward to allow the R_{so} to fit the upper envelope of measured R_s data that have been plotted over time. However, the measured data should be shown to be traceable to the international standard for R_s within the previous year.

For hourly or shorter periods ϕ is calculated as:

$$\sin \phi = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega \quad (2-4)$$

where: φ latitude [rad]
 δ solar declination [rad]
 ω solar time angle at midpoint of hourly or shorter period [rad]

For 24-hour periods, the mean daily sun angle, weighted according to R_a , can be approximated as:

$$\sin \phi_{24} = \sin \left[0.85 + 0.3\varphi \sin \left(\frac{2\pi}{365} J - 1.39 \right) - 0.42\varphi^2 \right] \quad (2-5)$$

where: ϕ_{24} average ϕ during the daylight period, weighted according to R_a [rad]
 φ latitude [rad]
 J day in the year []

The ϕ_{24} variable is used to represent the average sun angle during daylight hours and has been weighted to represent integrated 24-hour transmission effects on 24-hour R_{so} . ϕ_{24} should be limited to ≥ 0 .

FAO56c method

In some situations, the estimation for R_{so} can be improved by considering the effects of water vapor on short wave absorption, so that:

$$R_{so} = (K_B + K_D) R_a \quad (2-6)$$

where: K_B the clearness index for direct beam radiation []
 K_D the corresponding index for diffuse beam radiation []
 R_a extraterrestrial radiation [$MJ\ m^{-2}\ d^{-1}$] or [$MJ\ m^{-2}\ h^{-1}$]

$$K_B = 0.98 \exp \left[\frac{-0.00146 P}{K_t \sin \phi} - 0.091 \left(\frac{W}{\sin \phi} \right)^{0.25} \right] \quad (2-7)$$

where: K_t turbidity coefficient [], $0 < K_t \leq 1.0$ where $K_t = 1.0$ for clean air and $K_t = 1.0$ for extremely turbid, dusty or polluted air.
 P atmospheric pressure [kPa]
 ϕ angle of the sun above the horizon [rad]
 W precipitable water in the atmosphere [mm]

$$W = 0.14 e_a P + 2.1 \quad (2-8)$$

where: W precipitable water in the atmosphere [mm]

$$\begin{array}{ll} e_a & \text{actual vapor pressure [kPa]} \\ P & \text{atmospheric pressure [kPa]} \end{array}$$

The diffuse radiation index K_D is estimated from K_B :

$$\begin{aligned} K_D &= 0.35 - 0.36 K_B && \text{for } K_B \geq 0.15 \\ K_D &= 0.18 + 0.82 K_B && \text{for } K_B < 0.15 \end{aligned} \quad (2-9)$$

ϕ_{24} from Equation (2-5) is used for ϕ in Equation (2-7) for 24-hour estimates of R_{SO} . The value "0.36" in Eq. 2-9 has replaced the value "0.33" that was formerly reported in Allen (1996) and FAO-56. However, the "0.36" value has been found to produce R_{SO} that is in closer agreement with the NREL standard in Boulder, Colorado, which is traceable to the International standard.

Ordinarily, R_{SO} computed using the R_{SO} equations will plot as an upper envelope of measured R_s and is useful for checking calibration of instruments. The turbidity parameter K_t in Equations 2-3 and 2-7 can be adjusted downward to allow the R_{SO} to fit the upper envelope of measured R_s data that have been plotted over time. However, the measured data should be shown to be traceable to the international standard for R_s within the previous year.

Extraterrestrial radiation for 24-hour periods (R_a)

The extraterrestrial radiation, R_a , for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year by:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)] \quad (2-10)$$

where

$$\begin{array}{ll} R_a & \text{extraterrestrial radiation [MJ m}^{-2} \text{ day}^{-1}\text{]}, \\ G_{sc} & \text{solar constant} = 0.0820 \text{ MJ m}^{-2} \text{ min}^{-1}, \\ d_r & \text{inverse relative distance Earth-Sun}, \\ \omega_s & \text{sunrise hour angle [rad]}, \\ \phi & \text{latitude [rad]}, \\ \delta & \text{solar declination [rad]}. \end{array}$$

R_a is expressed in the above equation in $\text{MJ m}^{-2} \text{ day}^{-1}$. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_a by 0.408 which is $1/\lambda$ in MJ/kg . The latitude, ϕ , expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degrees to radians is given by:

$$[\text{Radians}] = \frac{\pi}{180} [\text{decimal degrees}] \quad (2-11)$$

The inverse relative distance Earth-Sun, d_r , and the solar declination, δ , are given by:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (2-12)$$

$$\delta = 0.4093 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (2-13)$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December).

For daily values, the day of the year, J , can be calculated as:

$$J = D_M - 32 + \text{Int}\left(275 \frac{M}{9}\right) + 2 \text{ Int}\left(\frac{3}{M+1}\right) + \text{Int}\left(\frac{M}{100} - \frac{\text{Mod}(Y, 4)}{4} + 0.975\right) \quad (2-14)$$

where D_M the day of the month (1-31),
 M the number of the month (1-12)
 Y the number of the year (for example 1996 or 96).

The "Int" function finds the integer number of the argument in parentheses by rounding downward. The "Mod(Y,4)" function finds the modulus (remainder) of the quotient $Y/4$. The last "Int" term of Eq. 1-14 can be omitted when the effect of leap years is to be ignored, so that $J = D_M - 32 + \text{Int}(275 M/9) + 2 \text{ Int}(3/(M+1))$. REF-ET uses a "look up" table to compute J , rather than the above equation.

For monthly periods, the day of the year at the middle of the month is approximately:

$$J_{\text{month}} = \text{Int}(30.4 M - 15) \quad (2-15)$$

The sunset hour angle, ω_s , is given by:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (2-16)$$

As the arccos function is not available in all computer languages, the sunset hour angle can also be computed using the arctan function:

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right] \quad (2-17)$$

where

$$X = 1 - [\tan(\varphi)]^2 [\tan(\delta)]^2 \quad (2-18)$$

and $X = 0.00001$ if $X \leq 0$

Extraterrestrial radiation for hourly or shorter periods (R_a)

For hourly or shorter periods the solar time angle at the beginning and end of the period should be considered when calculating R_a :

$$R_a = \frac{12 (60)}{\pi} G_{sc} d_r [(\omega_2 - \omega_1) \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) (\sin(\omega_2) - \sin(\omega_1))] \quad (2-19)$$

where R_a extraterrestrial radiation in the hour (or shorter) period [$\text{MJ m}^{-2} \text{ hour}^{-1}$],
 G_{sc} solar constant = $0.0820 \text{ MJ m}^{-2} \text{ min}^{-1}$,
 d_r inverse relative distance Earth-Sun,
 δ solar declination [rad],
 ϕ latitude [rad],
 ω_1 solar time angle at beginning of period [rad],
 ω_2 solar time angle at end of period [rad].

The solar time angles at the beginning and end of the period are given by:

$$\omega_1 = \omega - \frac{\pi t_1}{24} \quad (2-20)$$

$$\omega_2 = \omega + \frac{\pi t_1}{24} \quad (2-21)$$

where ω solar time angle at midpoint of hourly or shorter period [rad],
 t_1 length of the calculation period [hour]: i.e., 1 for hourly period or 0.5 for a 30-minute period.

The solar time angle at midpoint of the period is:

$$\omega = \frac{\pi}{12} [(t + 0.06667(L_z - L_m) + S_c) - 12] \quad (2-22)$$

where t standard clock time at the midpoint of the period [hour]. For example for a period between 14.00 and 15.00 hours, $t = 14.5$,
 L_z longitude of the centre of the local time zone [degrees west of Greenwich]. For example, $L_z = 75, 90, 105$ and 120° for the Eastern, Central, Rocky Mountain and Pacific time zones (United States) and $L_z = 0^\circ$ for Greenwich, 330° for Cairo (Egypt), and 255° for Bangkok (Thailand),
 L_m longitude of the measurement site [degrees west of Greenwich],
 S_c seasonal correction for solar time [hour].

The seasonal correction for solar time is:

$$S_c = 0.1645 \sin(2b) - 0.1255 \cos(b) - 0.025 \sin(b) \quad (2-23)$$

$$b = \frac{2\pi (J - 81)}{364} \quad (2-24)$$

where J is the number of the day in the year.

It is important that the values for both ω_1 and ω_2 in Equation 2-19 be within the range of $-\omega_s$ to $+\omega_s$ (daylight period). When the values for ω_1 and ω_2 span the value for $-\omega_s$ or ω_s ($-\omega_s$ is the sunrise hour angle), this indicates that sunrise or sunset occurs within the hourly (or shorter) period. In this case, the integration limits for applying Equation 2-19 are set using the following conditionals:

```

If  $\omega_1 < -\omega_s$  then  $\omega_1 = -\omega_s$ 
If  $\omega_2 < -\omega_s$  then  $\omega_2 = -\omega_s$ 
If  $\omega_1 > \omega_s$  then  $\omega_1 = \omega_s$ 
If  $\omega_2 > \omega_s$  then  $\omega_2 = \omega_s$ 
```

Also, the requirement that $\omega_1 \leq \omega_2$ is enforced. The above conditionals insure numerical stability of the application of Equation 2-19 as well as correctly computing any theoretical quantities of solar radiation early and late in the day. If the hour is completely beyond sunrise or sunset (i.e., nighttime), then both ω_1 and ω_2 are set to values that are equal to ω_s , so that the integration in 2-19 becomes 0.

Equations 2-16 to 2-21 presume an infinitely flat ground surface. Where there are hills or mountains, the hour angle when the sun first appears or disappears will increase for sunrise or decrease for sunset and the theoretical estimate for R_a from the above equations will have some error. Also, these calculations do not account for diffuse radiation occurring shortly before sunrise and shortly after sunset. Scattering of light at low angles plus effects of terrain along the horizon reduce the accuracy of the R_{so} estimate early and late in the day. Manufacturers of pyranometers would argue that the cosine error of the instrument also impacts the accuracy of the R_s reading at low sun angles. Therefore, the prediction of R_{so} and R_s/R_{so} at low sun angles is uncertain.

Solar radiation (R_s)

If the solar radiation, R_s , is not measured, it can be calculated for 24-hour or larger periods with the Angstrom formula that relates R_s to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \quad (2-25)$$

where	R_s	solar or shortwave radiation [$MJ\ m^{-2}\ day^{-1}$],
	n	actual duration of sunshine [hour],
	N	maximum possible duration of sunshine or daylight hours [hour],
	n/N	relative sunshine duration [-],
	R_a	extraterrestrial radiation [$MJ\ m^{-2}\ day^{-1}$],
	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 ($n = N$).

R_s is expressed in the above equation in $MJ\ m^{-2}\ day^{-1}$. Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values $a_s = 0.25$ and $b_s = 0.50$ are recommended. In REF-ET, it is assumed that $a_s = 0.25$ and $b_s = 0.50$, following FAO-24 and FAO-56.

Daylight hours (N)

The potential daylight hours, N, are given by:

$$N = \frac{24}{\pi} \omega_s \quad (2-26)$$

where ω_s is the sunset hour angle in radians.

Wind profile relationship

Wind speeds measured at different heights above the soil surface are different. Surface friction tends to slow down wind passing over it. Wind speed is slowest at the surface and increases with height. For this reason anemometers are placed at a chosen standard height, i.e., 10 m in meteorology and 2 or 3 m in agrometeorology. For the calculation of the FAO-56 Penman-Monteith, Kimberly Penman, FAO-34 Penman and CIMIS Penman equations, wind speed measured at 2 m above the surface is required. To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2 m, a logarithmic wind speed profile is used in REF-ET:

$$u_2 = u_z \frac{\ln\left(\frac{2-d}{z_{om}}\right)}{\ln\left(\frac{z_w-d}{z_{om}}\right)} \quad (2-27)$$

where u_2 wind speed at 2 m above ground surface for the reference vegetation [$m s^{-1}$],
 u_z measured wind speed at z_w m above ground surface of weather station [$m s^{-1}$],
 z_w height of measurement above ground surface [m],
 d zero plane displacement height for the weather site vegetation, m, ($d = 0.67$ h)
 z_{om} aerodynamic roughness length for the weather site vegetation, m, ($z_{om} = 0.123$ h)

For measurements above a short grassed surface, Eq. 2-27 reduces to:

$$u_2 = u_z \frac{4.87}{\ln(67.8 z_w - 5.42)} \quad (2-28)$$

In REF-ET, u_2 is computed using Eq. 2-27, where roughness height, z_{om} is based on 0.12 m clipped grass, regardless of the reference crop that is specified, whereas, zero plane displacement height, d , is based on the height of the weather surface vegetation. If the height of the weather surface vegetation is not specified, then d is based on the height of the reference crop. This is why two values for d and u_2 are listed in the intermediate file (.IN2), since they may vary with the reference crop if the height is read from the data file. This implies to REF-ET that the wind measurements may have been made over the reference surface.

Daylight Savings Time

In the United States, since about 1917, daylight savings time has been observed in some states. The use of DST, where the true clock time is shifted by one hour, impacts the computation of extraterrestrial radiation in the case of hourly (or shorter) time steps. Therefore, when hourly data are evaluated by REF-ET, the user should indicate on Definition screen 1 (Fig. 5) whether DST was observed for that particular year and location. The following “rules” are observed in REF-ET if the DST box is “checked”:

- For 1918 to 1941, the time was shifted one hour later from the last Sunday in April until the last Sunday in October.
- From DoY 40 of 1942 until DoY 263 of 1945, time was shifted one hour later under DST.
- For 1946 to 1973, the time was shifted one hour later from the last Sunday in April until the last Sunday in October.
- In 1975, the time was shifted one hour later from January 6 until the last Sunday in October.
- In 1976, the time was shifted one hour later from DoY 54 until the last Sunday in October.
- For 1977 to 1986, the time was shifted one hour later from the last Sunday in April until the last Sunday in October.
- From 1987 to present, the time was shifted one hour later from the first Sunday in April until the last Sunday in October.

The occurrence of DST, if indicated by the user, is corrected for during the calculation of extraterrestrial radiation and sunset hour angle. However, the value for the hour is not changed when results are printed out. These values for time are kept the same as the values that were read in from the data file to reduce confusion.

Appendix 3

Estimating Missing Climatic Data

The calculation of the reference evapotranspiration ET_0 with the Penman or Penman-Monteith methods requires mean hourly, daily, ten-day or monthly maximum and minimum air temperature (T_{\max} and T_{\min}), actual vapor pressure (e_a), net radiation (R_n) and wind speed measured at 2 m (u_2). If some of the required weather data to calculate these parameters are missing or lack integrity, it is recommended that the user estimate the missing climatic data with one of the following procedures from FAO-56.

Minimum data requirements

This appendix provides recommendations on how solar radiation, vapor pressure and wind data can be estimated when missing. Many of the suggested procedures rely upon maximum and minimum air temperature measurements. Unfortunately, there is no dependable way to estimate air temperature data when they are missing. Therefore it is suggested that maximum and minimum daily air temperature data are the minimum data requirements necessary to apply the Penman-Monteith and Penman methods.

Estimating missing humidity data

Where humidity data are lacking or are of questionable quality, an estimate of actual vapor pressure, e_a , can be estimated for irrigated or well-watered conditions by assuming that dewpoint temperature (T_{dew}) is near the daily minimum temperature (T_{\min}):

$$T_{dew} = T_{\min} - K_0 \quad (3-1)$$

where K_0 is approximately 2 °C in dry (arid and semiarid) climates and K_0 is approximately 0 °C in humid to subhumid climates.

This relationship implicitly presumes that at sunrise, when the air temperature is close to T_{\min} , that the air over the well-watered or irrigated surface is nearly saturated with water vapor and the relative humidity is nearly 100%. The relationship holds for locations where the cover crop of the station is well watered. In humid and subhumid climates, T_{\min} and T_{dew} measured in early morning may be less than T_{dew} measured during the daytime because of condensation of dew during the night. After sunrise, evaporation of the dew will once again humidify the air and will increase the value measured for T_{dew} during the day time. However, it is generally standard practice in 24-hour calculations of ET_0 to use T_{dew} measured or calculated during early morning.

Application of Eq. 3-1 rather than using actual measurements of T_{dew} or RH_{\min} in situations where the weather station has known, severe aridity (lack of well-watered condition and vegetation) can improve the calculation of ET_0 , which is defined as representing ET in a well-watered environment. Further information and recommendations are given in FAO-56 and in the article on integrity assessment by Allen (1996, ASCE).

Estimating missing radiation data

Solar Radiation data from a nearby weather station

For the same month and often for the same day, the variables affecting incoming solar radiation, R_s , and sunshine duration, n , are similar throughout a given region. This implies that: (i) the size of the region is small; (ii) the air masses governing rainfall and cloudiness are nearly identical within parts of the region; and (iii) the physiography of the region is almost homogenous. Differences in relief should be negligible as they strongly influence the movement of air masses. Under such conditions, radiation data observed at nearby stations can be used.

Where the north-south distance to a weather station within the same homogeneous region exceeds 50 km so that the value for R_a changes, the R_s measurement should be adjusted using the ratio of the solar to extraterrestrial radiation, R_s/R_a :

$$R_s = \frac{R_{s,reg}}{R_{a,reg}} R_a \quad (3-2)$$

where $R_{s,reg}$ solar radiation at the regional location [$\text{MJ m}^{-2} \text{ day}^{-1}$],
 $R_{a,reg}$ extraterrestrial radiation at the regional location [$\text{MJ m}^{-2} \text{ day}^{-1}$].

The estimation method of Equation 3-2 is recommended for weekly to monthly calculations of ET_0 . If using the method for daily estimates of ET_0 , a more careful analysis of weather data in the importing and exporting meteorological stations has to be performed to verify whether both stations are in the same homogeneous climatic region and are close enough to experience similar conditions within the same day. The analysis should include the comparison of daily weather data from both stations, particularly the maximum and minimum air temperature and humidity. In fact, similar cloudiness and sunshine durations are related to similarities in temperature and humidity trends. Equation 3-2 is not employed in REF-ET.

Generally, daily calculations of ET_0 with estimated radiation data are justified when utilized as a sum or an average over a several-day period. This is the case for the computation of the mean evapotranspiration demand between successive irrigations or when planning irrigation schedules. Under these conditions, the relative error for one day often counterbalances the error for another day of the averaging period. Daily estimates should not be utilized as true daily estimates but only in averages over the period under consideration.

Solar Radiation data derived from air temperature differences

The difference between the maximum and minimum air temperature is related to the degree of cloud cover in a location. Clear-sky conditions result in high temperatures during the day (T_{\max}) because the atmosphere is transparent to the incoming solar radiation and in low temperatures during the night (T_{\min}) because less outgoing longwave radiation is absorbed by the atmosphere. On the other hand, in overcast conditions, T_{\max} is relatively smaller because a significant part of the incoming solar radiation never reaches the earth's surface and is absorbed and reflected by the clouds. Similarly, T_{\min} will be relatively higher as the cloud cover acts as a blanket and decreases the net outgoing longwave radiation. Therefore, the difference between the maximum and minimum air temperature ($T_{\max} - T_{\min}$) can be used as an indicator of the fraction of extraterrestrial radiation that

reaches the earth's surface. This principle has been utilized by Hargreaves and Samani to develop estimates of ET_0 using only air temperature data.

The Hargreaves' radiation formula, adjusted and validated at several weather stations in a variety of climate conditions, becomes:

$$R_s = k_{Rs} \sqrt{(T_{max} - T_{min})} R_a \quad (3-3)$$

where R_a extraterrestrial radiation [$MJ\ m^{-2}\ d^{-1}$],
 T_{max} maximum air temperature [$^{\circ}C$],
 T_{min} minimum air temperature [$^{\circ}C$],
 k_{Rs} adjustment coefficient ($0.16 \dots 0.19$) [$^{\circ}C^{-0.5}$].

The adjustment coefficient k_{Rs} is empirical and differs for 'interior' or 'coastal' regions:

- for 'interior' locations, where land mass dominates and air masses are not strongly influenced by a large water body, $k_{Rs} \approx 0.16$;
- 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, $k_{Rs} \approx 0.19$.

R_s predicted by Equation 3-3 should be limited to $\leq R_{so}$. The temperature difference method is recommended for locations where it is not appropriate to import radiation data from a regional station, either because homogeneous climate conditions do not occur, or because data for the region are lacking. For island conditions, the methodology is not appropriate due to moderating effects of the surrounding water body.

Caution is required when daily computations of ET_0 are needed. It is recommended that daily estimates of ET_0 that are based on estimated R_s be summed or averaged over a several-day period, such as a week, decade or month to reduce prediction error.

Empirical methodology for island locations

For island locations, defined as where the land mass has a width perpendicular to the coastline of 20 km or less, the air masses influencing the atmospheric conditions are dominated by the adjacent water body in all directions. The temperature method is not appropriate for this situation. Where radiation data from another location on the island are not available, a first estimate of the monthly solar average can be obtained from the empirical relation:

$$R_s = 0.7 R_a - b \quad (3-4)$$

where R_s solar radiation [$MJ\ m^{-2}\ day^{-1}$],
 R_a extraterrestrial radiation [$MJ\ m^{-2}\ day^{-1}$],
 b empirical constant, equal to $4\ MJ\ m^{-2}\ day^{-1}$.

This relationship is only applicable for low altitudes (from 0 to 100 m). The empirical constant represents the fact that in island locations some clouds are usually present, thus making the mean solar radiation $4\ MJ\ m^{-2}\ day^{-1}$ below the nearly clear sky envelope ($0.7\ R_a$). Local adjustment of the empirical constant may improve the estimation. The method is only appropriate for monthly calculations. The constant relation between R_s and R_a does not yield accurate daily estimates.

Missing wind speed data

Wind speed data from a nearby weather station

Importing wind speed data from a nearby station, as for radiation data, relies on the fact that the air flow above a 'homogeneous' region may have relatively large variations through the course of a day but small variations when referring to longer periods or the total for the day. Data from a nearby station may be imported where air masses are of the same origin or where the same fronts govern air flows in the region and where the relief is similar.

When importing wind speed data from another station, the regional climate, trends in variation of other meteorological parameters and relief should be compared. Strong winds are often associated with low relative humidity and light winds are common with high relative humidity. Thus, trends in variation of daily maximum and minimum relative humidities should be similar in both locations. In mountainous areas, data should not necessarily be imported from the nearest station but from nearby stations with similar elevation and exposure to the dominant winds. The paired stations may even vary from one season to another, depending on the dominant winds.

Imported wind speed data can be used when making monthly estimates of evapotranspiration. Daily calculations are justified when utilized as a sum or average over a several-day period, such as a week or decade.

Empirical estimates of monthly wind speed

As the variation in wind speed average over monthly periods is relatively small and fluctuates around average values, monthly values of wind speed may be estimated. The 'average' wind speed estimates may be selected from information available for the regional climate, but should take seasonal changes into account. General values are suggested in Table 3-1.

TABLE 3-1
General classes of monthly wind speed data (from FAO-56)

Description	mean monthly wind speed at 2 m
light wind	... ≤ 1.0 m/s
light to moderate wind	1 – 3 m/s
moderate to strong wind	3 – 5 m/s
strong wind	... > 5.0 m/s

Where no wind data are available within the region, a value of 2 m/s can be used as a temporary estimate. This value is the average over 2 000 weather stations around the globe.

In general, wind speed at 2 m, u_2 , should be limited to about $u_2 \geq 0.5$ m/s when used in the Penman-Monteith ET_O equation. This is necessary to account for the effects of boundary layer instability and buoyancy of air in promoting exchange of vapor at the surface when air is calm. This effect occurs when the wind speed is small and buoyancy of warm air induces air exchange at the surface. Limiting $u_2 \geq 0.5$ m/s in the ET_O equation improves the estimation accuracy under the conditions of very low wind speed.

If daytime wind speed (used in the FAO Blaney-Criddle, FAO Penman and FAO Radiation methods) is not entered into REF-ET, then daytime wind speed is estimated from 24-hour wind speed and day/night wind ratio (7am to 7pm) as:

$$U_d = 2 * U_{24} / (1 + 1 / DNR) \quad (3-5)$$

where DNR is the day to night wind ratio, U_d is the day time wind speed, m/s, and U24 is 24-hour wind speed, m/s. If DNR is not entered into REF-ET, then its value is set equal to the default value which is entered on the second definition file editing screen.

If both daytime wind speed and 24-hour wind speed are entered into REF-ET, then the day to night wind ratio (used in the FAO Corrected Penman method) is estimated as:

$$DNR = U_d / (2 * U24 - U_d) \quad (3-6)$$

Predicting Maximum and Minimum Air Temperature from Mean Air Temperature

Occasionally daily or monthly weather data sets contain measurements for solar radiation, wind speed, and relative humidity or dewpoint temperature, but contain only information on mean daily air temperature, T_{mean} , with no data for T_{max} and T_{min} . T_{max} and T_{min} are required for proper application of the Penman-Monteith and Kimberly Penman equations, since they are required in the estimation of mean saturation vapor pressure (Eq. 16) and net outgoing long-wave radiation (Eq. 26). REF-ET sets T_{max} and T_{min} equal to T_{mean} in these situations, but the user should be aware that the difference $e_s - e_a$ in the Penman-Monteith and Kimberly Penman equations (Eq. 1, 36, and 37 and 39) will be underpredicted and R_n may be overpredicted.

A “crude” method for predicting values for T_{max} and T_{min} that can be used in REF-ET to improve the estimates of e_s and R_n is to invert a Hargreaves type of equation (i.e., Eq. 3-3) for predicting R_s :

$$(\hat{T}_{max} - \hat{T}_{min}) = \left(\frac{1}{k} \frac{R_s}{R_a} \right)^2 \quad (3-7)$$

where all terms and units are defined as in Eq. 3-3. T_{max} and T_{min} are then predicted as:

$$\hat{T}_{max} = T_{mean} + \frac{(\hat{T}_{max} - \hat{T}_{min})}{2} \quad (3-8)$$

$$\hat{T}_{min} = T_{mean} - \frac{(\hat{T}_{max} - \hat{T}_{min})}{2} \quad (3-9)$$

This prediction of T_{max} and T_{min} requires that R_s data be available in the data set. This prediction of T_{max} and T_{min} is not done inside of REF-ET. Therefore, the user must make these predictions outside the program before running REF-ET. The user should be careful that T_{max} and T_{min} as predicted using Eq. 3-7 to 3-9 are carefully marked in any data files or reports as estimated, so that they are not later used as real data by other users.

Appendix 4

Converting between Reference Types

Reference Ratios

The two basic standard vegetation references for evapotranspiration are the cool season clipped grass and full cover alfalfa. Unfortunately, due to the smoothness of the grass reference, the ratio between these two references may change with climate, mostly due to effects of windiness and dryness of the aerodynamic responses of the surfaces.

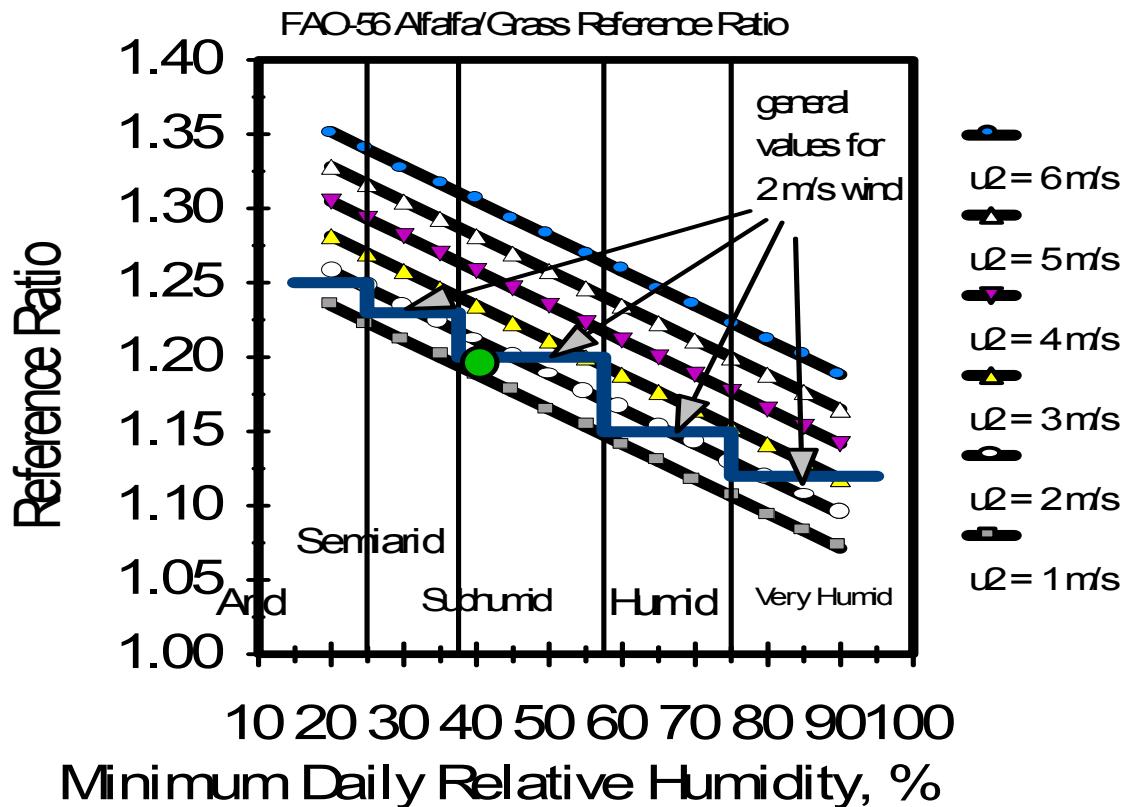
The FAO-56 recommends converting between alfalfa and grass references by applying the generalized climatic corrections that are used in FAO 56 for all crops:

$$ET_r/ET_0 = 1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{0.5}{3} \right)^{0.3} \quad (4-1)$$

where u_2 is wind speed at 2 m in m/s and RH_{min} is mean daily minimum relative humidity, %. The 0.5 in the equation is the general height of the alfalfa reference. The 1.2 value is the general crop coefficient for full cover alfalfa under a standard FAO-56 climate ($RH_{min} = 45\%$ and $u_2 = 2 \text{ m s}^{-1}$).

The FAO-56 equation is intended to be applied using general means for a location, perhaps on a seasonal basis (winter, spring, summer, fall). One does not need to compute the ratio daily. Also, general values of u_2 and RH_{min} for the mid part of the growing season are generally acceptable. The following figure demonstrates how the reference ratio varies with general climate.

For the standard FAO-56 climate (subhumid, low to moderate wind speed) ($RH_{min} = 45\%$ and $u_2 = 2 \text{ m s}^{-1}$), the ratio of ET_r/ET_0 is 1.20. For other climates having $u_2 = 2 \text{ m s}^{-1}$, the ratio would range from 1.25 for arid, to 1.23 for semiarid, to 1.20 for subhumid, to 1.15 for humid, to 1.10 to very humid. These ratios would increase for higher levels of wind speed as indicated in the following figure.



An alternative to computing ET_r/ET_o using Eq. 4-1 is to simply apply both ET_r and ET_o equations to weather data and take the ratio of the estimates. This ratio would then be used to adjust crop or cover coefficients between the two references. However, because weather measurements over a single surface (normally grass) do not include the feedback effects of higher ET from alfalfa as opposed to ET from grass, applying this second alternative may over estimate the actual ratio of ET_r/ET_o .

REF-ET uses a user-supplied ratio of ET_r/ET_o to convert the ET_o based equations: 1998 FAO-PM, 1963 Penman, all FAO-24 equations, Priestley-Taylor, Makkink, Hargreaves, and Turc to ET_r . It uses this ratio to convert the 1972 Kimberly Penman ET_r equation to ET_o . This ratio can be based on Eq. 4-1 or other known relationships. No ET_r/ET_o ratio is needed with the ASCE PM equations, since these equations can be applied to either reference.

Appendix 5

Weather Data Integrity Assessment

ET_o and ET_r estimates are only as good as the weather data used in their estimation. Weather data should be screened to insure integrity and representativeness. This is especially important with electronically collected data, since human oversight and maintenance may be limited.

Solar Radiation

Solar radiation data can be screened by plotting measurements against clear sky R_{so} envelopes for both hourly and daily periods (Allen 1996). This is done using Eqns. 2-3 or 2-6. Both of these calculations are made by REF-ET and are included in the IN2 intermediate file. For daily data, one should plot measured R_s and computed R_{so} from REF-ET against the day of the year. For hourly data, one should plot measured R_s and computed R_{so} against time of day, for one day at a time, for perhaps five or ten selected days.

One can make the graphs of R_s and R_{so} fairly easily from REF-ET files by importing both the "output" file (containing measured R_s) and the IN2 file into a common spreadsheet. Graphs can be created using the Day of Year as the X-axis for daily and using time of day as the X-axis for hourly. After creating the plots, the user should observe whether measured R_s "bumps" up against the clear sky envelope some of the time. R_s will fall below the clean sky curve on cloudy or hazy days and during parts of the year when the atmosphere is more turbid than under clear air conditions (i.e., following a cleansing rain or snow shower). If the "upper" values of measured R_s are routinely above or below the R_{so} curve by more than say 3 to 5%, then this should give cause to scrutinize the maintenance and calibration of the R_s sensor more closely. The pyranometer may need calibration or it may not be in perfect level or it may have been impacted by dust, salt, or bird droppings.

The R_{so} curves that are computed by Eq. 2-3 and 2-6 are not "perfect." They assume clean air and common relationships between the diffuse and beam components of short wave radiation along with typical spectral densities in the short wave band. However, these algorithms may not always apply so that one should exercise caution in using them to calibrate a pyranometer.

Net Radiation

Where net radiation data are measured, values should be compared to R_n that is estimated from solar radiation. Estimates of R_n from both the FAO-56 procedure and from the procedure of Wright (1982) are included in the IN2 file. These values can be imported into a spreadsheet along with the REF-ET output file containing measured R_n and the measured and estimated can be plotted vs. time. One should not expect measured R_n to exactly agree with estimated R_n . However, significant variation between the two should be cause for a closer look at the measured data. Many net radiometers have difficulty in accurately measuring the long wave component of net radiation. A change in the differences between measured and estimated R_n with time may indicate a change in the quality of the measurements due to scratched or dirty domes, off-level sensor, or condensation of moisture inside the domes of the R_n sensor, or positioning of the sensor over a surface that is different than the defined grass or alfalfa references.

Humidity and Air Temperature

Humidity data (T_d , RH, e_a) can be evaluated by examining daily maximum RH (RH_{max}) or by comparing T_d with T_{min} . Under reference conditions, RH_{max} generally approaches 100% during early morning and T_d approaches T_{min} (Allen 1996). Therefore, one should scan daily output tables from

REF-ET to note whether T_d is routinely in the neighborhood of T_{min} . If it isn't, then one should begin to scrutinize the maintenance and calibration of the RH or T_d equipment and impacts of the aridity of the weather site. A plot of T_d vs. T_{min} can be made by importing the daily output file from REF-ET into a spreadsheet and graphing.

Weather data should be representative of the reference condition. Data collected at or near airports can be negatively influenced by the local aridity, especially in arid and semiarid climates. Data from dry or urban settings may cause overestimation of ET_o or ET_r due to air temperature measurements that are too high and humidity measurements that are too low, relative to the reference condition. Allen and Pruitt (1986) and Allen (1996) suggested simple adjustments for "nonreference" weather data to provide data more reflective of well-watered settings. Allen and Gichuki (1989) and Ley et al. (1996) have suggested more sophisticated approaches. Annex 6 of FAO-56 also includes procedures for evaluating and correcting humidity and air temperature data for aridity of the weather site.

Often, substituting $T_d = T_{min} - K_{dew}$ for measured T_d , as suggested on page 25 and in the "missing data" window of REF-ET (Fig. 7), can improve ET_o estimates made with the combination equation when data are from a nonreference setting. Using the nonreference data will overestimate the true T_d and e_a that would occur under reference conditions, since T_{min} will be higher in the dry setting and consequently, so will estimated T_d . However, because e_s and e_a in the nonreference setting are both inflated when calculated using T_{max} , T_{min} and T_d estimated from T_{min} , the $e_s - e_a$ difference in the combination equation is often brought more in line with that expected for the reference condition and a more accurate estimate for ET_o results.

Similar to trends between T_d and T_{min} , one should expect daily RH_{max} to approach 100% RH during occasions of dewfall or significant rain. Dewfall often occurs in irrigated settings. Therefore, a plot of RH_{max} vs. day of the year should show values for RH_{max} that often approach 100%, or at least 90%. Deviation from this should be cause to scrutinize the RH data and sensor. RH_{max} can be plotted by importing the IN2 file into a spreadsheet.

Wind Speed

Accuracy of wind measurements is difficult to assess unless duplicate instruments are used. One should always scan wind records for the presence of consistently low wind recordings. For electronic instruments, these recordings may represent a numerical "offset" in the anemometer calibration equation. The presence of these constant and consistent offsets in the data set indicates either the presence of exceptionally calm conditions (wind speeds less than about 0.5 m s^{-1} during the entire sampling period (which is rare)) or a malfunctioning of the wind speed sensor due to electrical shorting or perhaps due to fatigue of bearings. These problems may not be noticed by the station operator.

When possible, a second anemometer¹¹ of the same design, but with fresh bearings, should be placed at the weather location for a three or four day period at least once each year, and recordings compared with the permanent instrument. Variations between recordings can signal a need to replace bearings, switches, or other parts.

¹¹ If a second data logger is used to record the temporary anemometer, one should be careful to synchronize data logger clocks. Also, one should be careful that anemometers do not interfere with one another's wind stream.