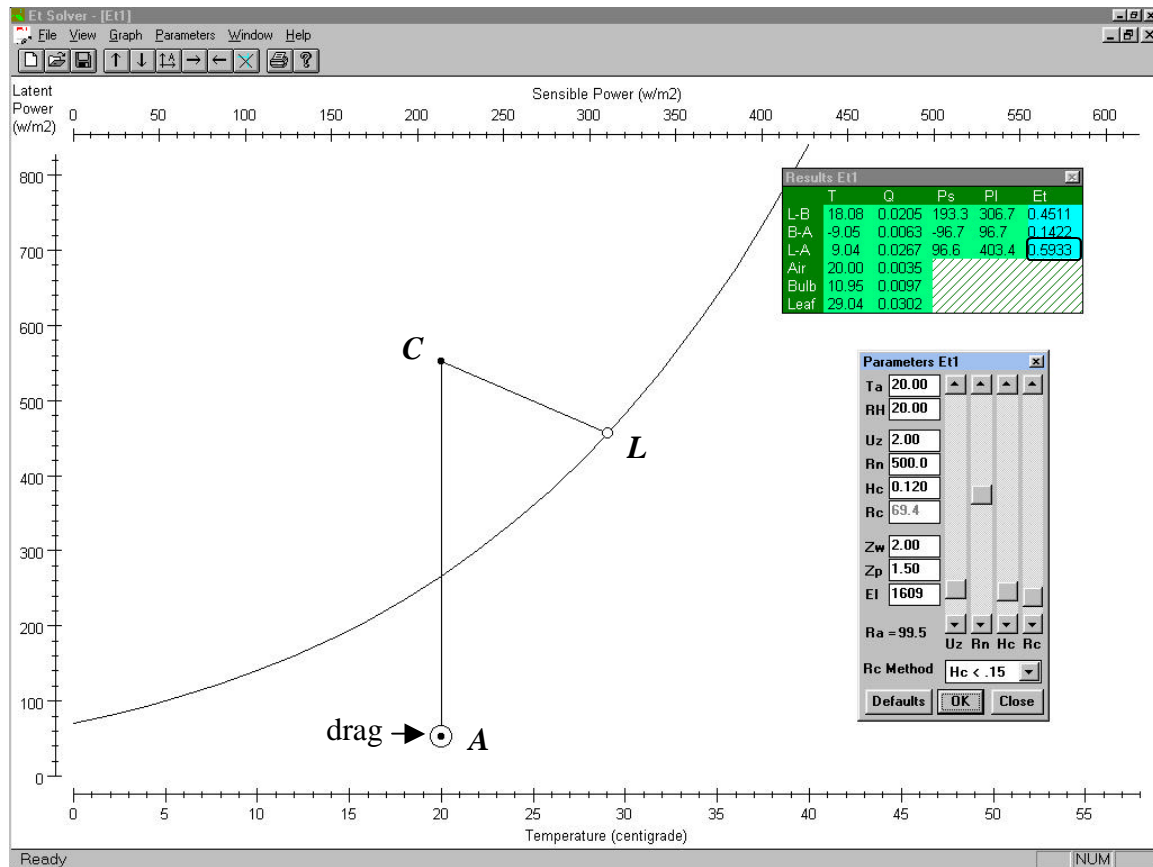# Et-Solver

   Et-Solver explores evapotranspiration problems with a graphical user interface. This program calculates Et using the Penman-Monteith model. It conforms to the methods and parameters used by *FAO-56 Penman* and the *ASCE Penman-Monteith* equations. Results from the program should also agree with the new *ASCE Standardized Reference Evapotranspiration Equation,* which was based on the *ASCE Penman-Monteith* with simplifying coefficients limiting crop height to "tall" or "short".

   Energy evaporates water. The flux of energy into new vapor is called latent power. If vapor condenses, it releases its energy as heat. Heat is sensible energy, and sensible power is the other major player in the Et equation. Power enters the system from the sun's radiation or by warming wind. Power leaves the system as water vapor, warmed air, or thermal radiation from plants and soil. Et is latent power expressed in watts per unit area. Et can also be expressed as the amount of water evaporated per unit time per unit area, which is depth of water per unit time.

   The graph on your screen will be a plot of latent power against sensible power. Et-Solver uses a power plane to show how available energy will be divided between evaporation and heating. Point *A* represents air at the elevation above ground where the weather station measured it. Point *L* represents saturated air inside a leaf. The vertical distance between point *A* and point *L* is latent power flowing from leaf to air, which is the Et rate expressed as power. You can see this power rate (W/m^2) and Et expressed as depth of water per time in the Results box: look in row "L-A" and columns Pl and Et. In like manner, sensible power flows between the air and the canopy of leaves. In the graph

temperature difference either on the bottom scale or in the Results box. Point C
theoretical significance. The vertical distance from A C is net radiation entering the

power goes into evaporating the leaf's moisture (latent power axis, L - A), and some goes
C, the Penman-Monteith model
L. To do this, the model needs values for the following:

Air temperature, T
2. Relative humidity, RH
3. The height above ground that T and RH were measured, Zp
4. Wind speed, Uz
5. The height above ground that wind speed was measured, Zw
6. Net radiation, Rn
7. Height of the leaf canopy, Hc
8. Elevation above sea level, El

You should enter these values in the "Parameters" box. Change two of the parameters,
air temperature and humidity, by simply dragging point A with your computer's mouse.
You can drag A to any temperature above freezing, but you cannot drag it below zero on
the latent power scale or above the upwardly curving vapor saturation curve. This is the
range of relative humidity from zero to 100% at saturation.

Installation

Et-Solver is a fast, simple, self-contained program that you can run under Microsoft
Windows directly from a floppy disk or from the hard drive. It does not require a setup
program or entry in the Windows registry. You can move Et.exe around on your hard
drive or delete it. No files will be left behind, with the exception of an "et.ini" file
explained below.

Save the program file, Et.exe, on your hard drive or on a floppy. To run, double-click
Et.exe or its icon in Program Manager, Windows Explorer, My Computer, etc. You can
also drag the icon onto Windows Desktop.

To un-install Et-Solver from your hard drive, simply delete it.

If you save a new set of default parameters (File|SaveDefaults in Et-Solver), a file
named "et.ini" will be created or updated in the Windows directory. It is very small, less
than 1KB. You can delete it at any time. If you do delete the et.ini file, the original
defaults will again be used by Et-Solver.

Getting Started

Start the program and maximize all windows. Use the left mouse button to drag the
Results box from the top of the screen to a convenient location. Now click on the circle
with the center dot, Point A, and drag it. Moving the point left or right changes air
temperature. Moving up or down changes relative humidity (0% at the bottom, 100% at
the saturation curve). As you move the point, you will see results calculated in the
Results Box.

Example 1

Click on **Parameters** on the menu bar, and drag the Parameters box to a convenient location. Enter the following parameters into the box by either highlighting the individual input controls with the cursor or by using the TAB key.

Ta 100.76	RH 19.6	Uz 2.36	Rn 259
Hc 0.12	Zw 2.00	Zp 1.50	El 285

Set the Rc Method to **Hc < .15**   Now click **OK**.

Click on **Graph** in the menu bar and select **Cross Hairs**; Temperature Units: **Fahrenheit** and Et Units: **inches/hour**. Then click OK.
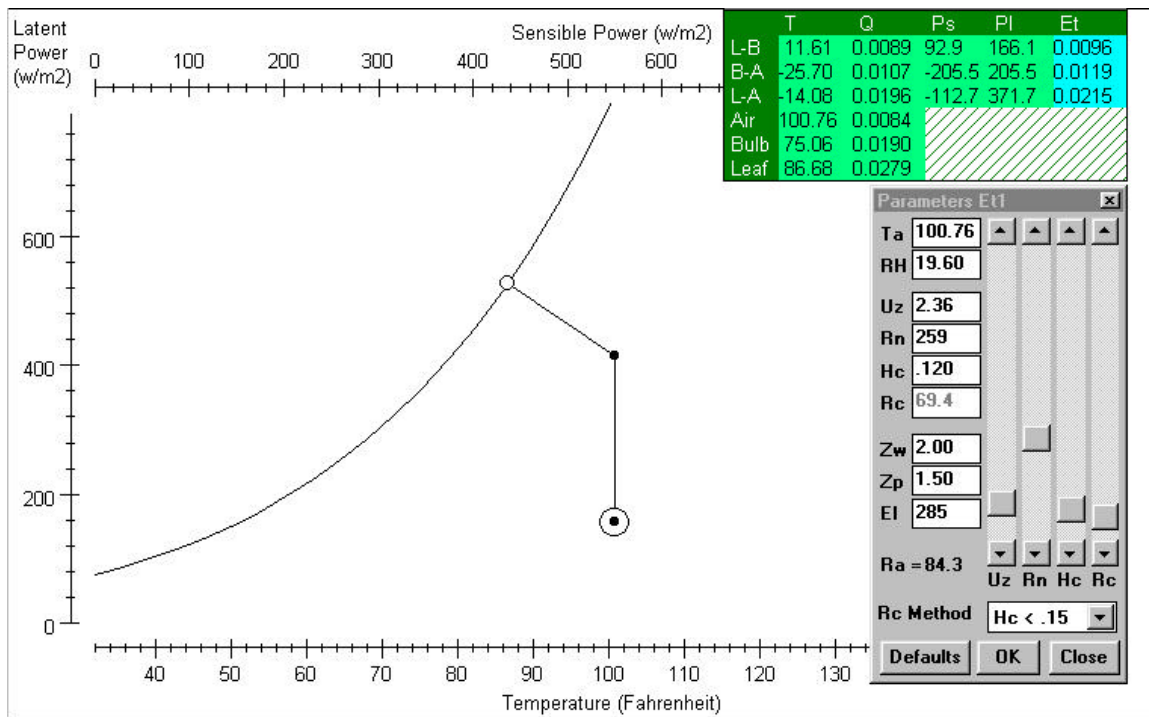
These were the conditions at 17:00 hours on June 10, 1994 at the West Side Field Station lysimeter site in Fresno, California. The Et rate was 0.0215 inches/hour. Note the air was 14° F hotter than the grass, a transient condition in late afternoon. See the next page for a twenty-four hour graph of that day. It compares rates and cumulative Et for the lysimeter, Et-Solver, Penman-Monteith (using the conventional algebraic equation), and CIMIS.

RATE mm/hr

Hour

CIMIS Eto

Lysimeter

T °C

Solar net radiation

Rel. Humidity

Et-Solver

Penman-Monteith
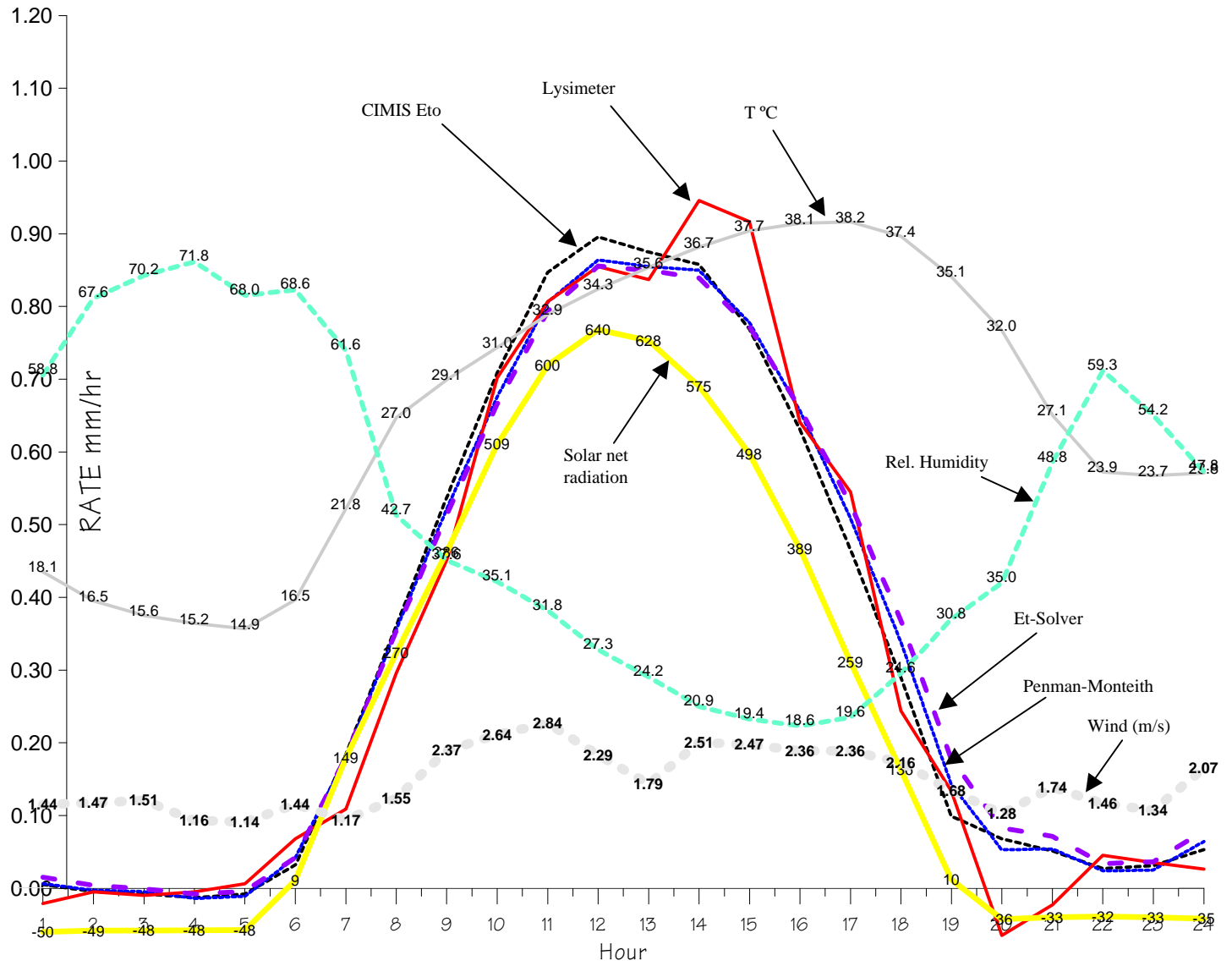
Wind (m/s)

FRESNO, CA
West Side Field Station
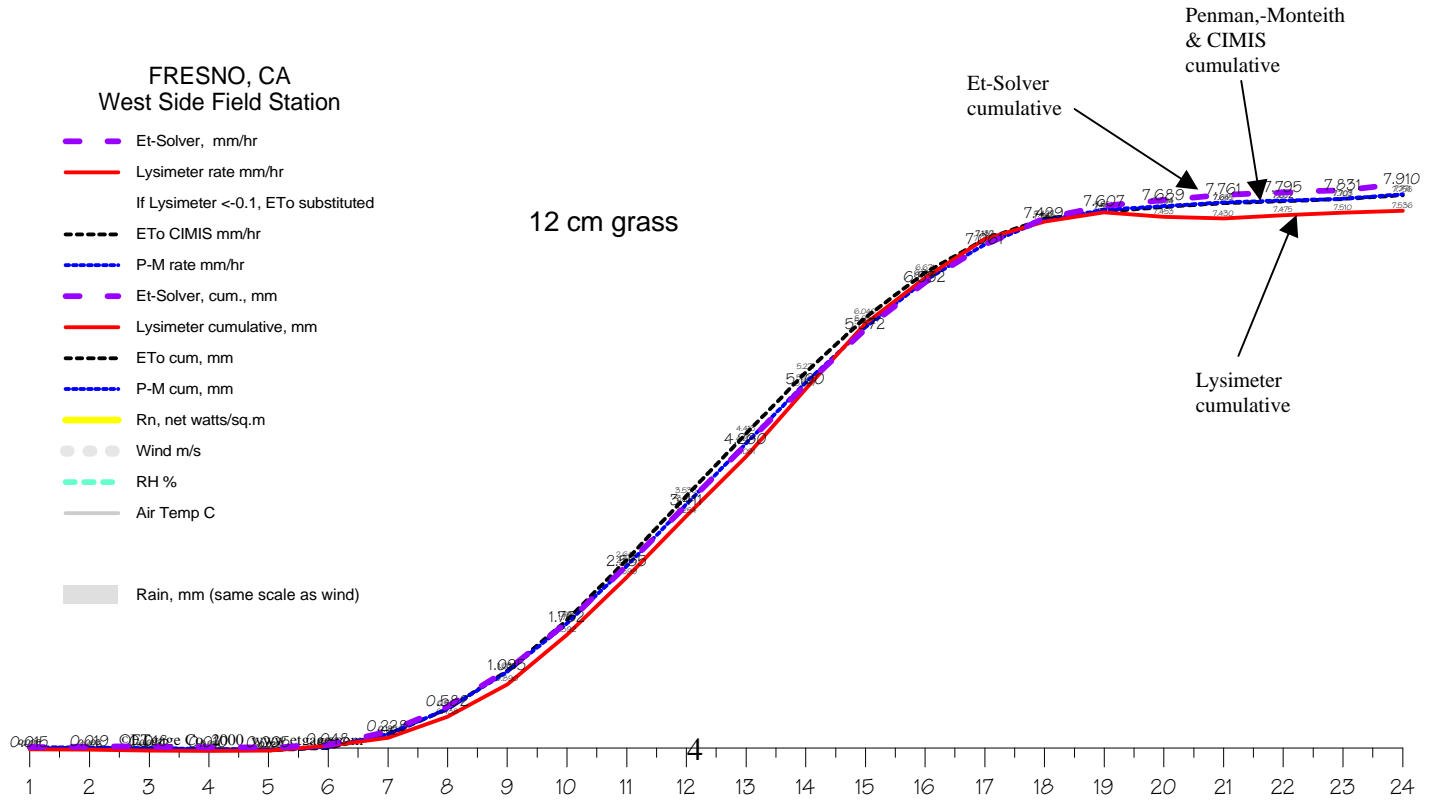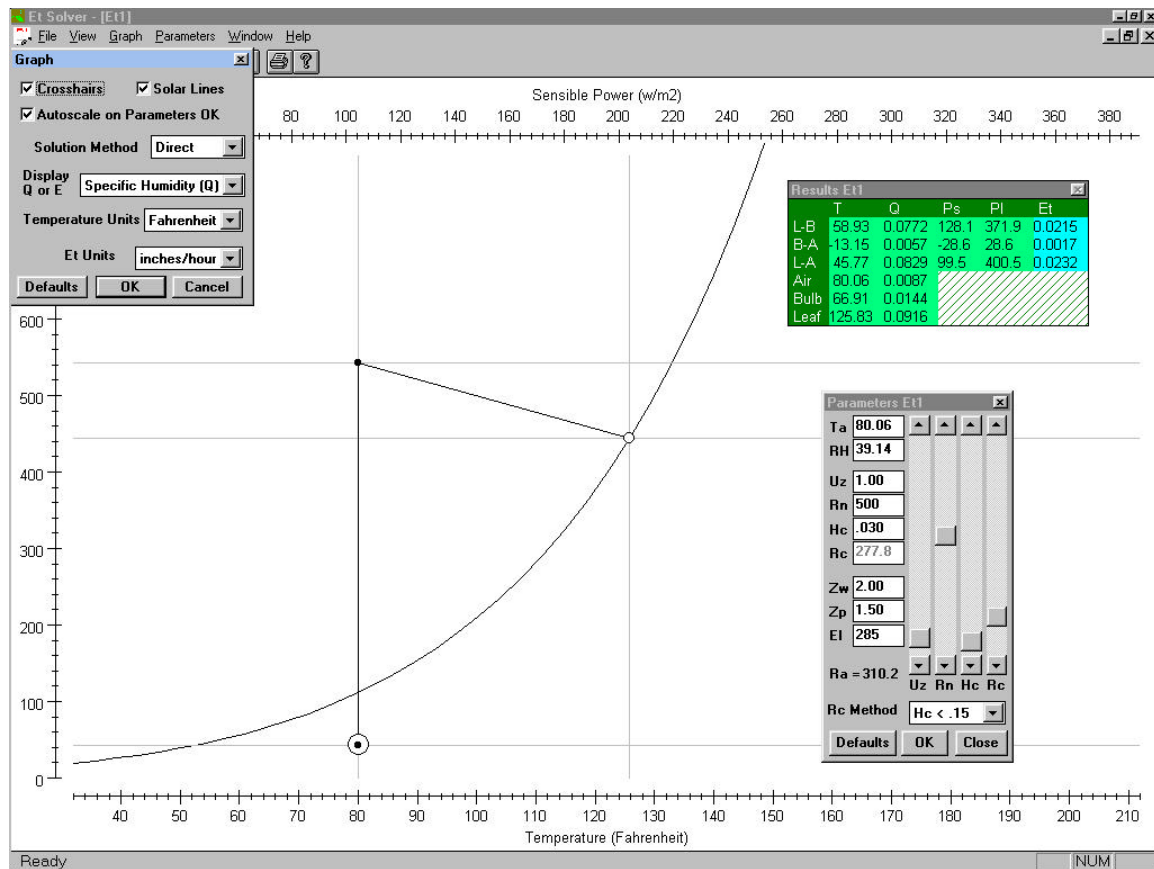
- Et-Solver, mm/hr
- Lysimeter rate mm/hr
- If Lysimeter <-0.1, ETo substituted
- ETo CIMIS mm/hr
- P-M rate mm/hr
- Et-Solver, cum., mm
- Lysimeter cumulative, mm
- ETo cum, mm
- P-M cum, mm
- Rn, net watts/sq.m
- Wind m/s
- RH %
- Air Temp C

- Rain, mm (same scale as wind)

12 cm grass

Penman,-Monteith & CIMIS cumulative

Et-Solver cumulative

Lysimeter cumulative

4

Example 2

In the graph above, this combination of weather conditions and grass height result in a very large temperature difference between leaf canopy and air at the weather station. Penman equations won't correctly model these conditions.

The graphical nature of Et-Solver can help alert you to such conditions. Here the Penman equation doesn't work well because the model assumes stable standard wind profiles. In the set of parameters above, very short grass (high canopy resistance) must get quite hot to dissipate summertime sunshine in a mild breeze. With this large temperature gradient, the atmosphere will not be stable. Thermals of hot air bubbling up through the atmospheric boundary layer increase vapor transport, increasing the Et rate above the calculated value.

Instructions

Et Solver - [Et1]

File View Graph Parameters Window Help

Latent
Power
(w/m2)

Sensible Power (w/m2)

0   200   400   600   800   1000   1200   1400   1600   1800   2000   2200   2400   2600

Results Et1

	T	Q	Ps	Pl	Et
L-B	5.69	0.0089	198.5	191.5	0.2816
B-A	-8.87	0.0140	-309.1	309.1	0.4546
L-A	-3.17	0.0228	-110.6	500.6	0.7363
Air	32.48	0.0079			
Bulb	23.61	0.0218			
Leaf	29.31	0.0307			

Drag boxes
from menu

Et (H_2O)
mm/hr

Parameters Et1

Ta 32.48
RH 21.67

Uz 6.53
Rn 390.0
Hc 0.120
Rc 85.9

Zw 2.00
Zp 1.50
El 1609

Ra = 30.5

Uz Rn Hc Rc

Rc Method Hc > .03

Defaults   OK   Close

L
leaf

C

Net
Radiation

Et (Latent Power)
Watts/m^2

Saturation
curve

Drag with
mouse

A
air

0   10   20   30   40   50   60

Temperature (centigrade)

Ready   NUM

RESULTS BOX

Et: Evapotranspiration. Units in mm/hour, mm/day, inches/hour or inches/day. See Graph Box below.

Pl: Latent heat power in watts/m^2.

Ps: Sensible heat power in watts/m^2.

Q: Specific humidity

or **E**: Vapor pressure in kPa.

T: Temperature in centigrade or Fahrenheit.

L: Leaf, or by extension, canopy of leaves.

A: Air at a point above the canopy where Ta and RH are measured by the weather station.

Results Et1

	T	Q	Ps	Pl	Et
L-B	5.69	0.0089	198.5	191.5	0.2816
B-A	-8.87	0.0140	-309.1	309.1	0.4546
L-A	-3.17	0.0228	-110.6	500.6	0.7363
Air	32.48	0.0079			
Bulb	23.61	0.0218			
Leaf	29.31	0.0307			

C: (See graph above) A construction point on the power plane. Assumes net radiation enters leaf moisture as latent power, then sensible power and latent power must adjust adiabatically to keep air saturated inside the leaves. To see the more usual presentation giving the same results, change Solution Method in the Graph menu from Direct to Combined.
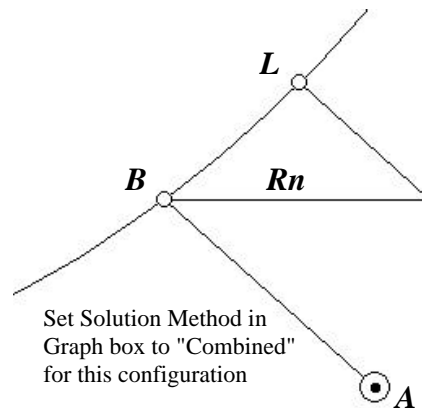
B: Shown in the display mode "Combined Solution Method", B is an important point in the Penman combination equation. For a wet evaporation surface, it is the "wet bulb" temperature point on the saturation curve. When Rn=0, B=L.

L-B: differential values.
B-A: differential values.
L-A: differential values.

Set Solution Method in Graph box to "Combined" for this configuration

PARAMETER BOX:

To open this box, select Parameters on the menu bar and drag the box to an open space.

Ta: Air temperature (°C or °F), at height Zp.
RH: Relative humidity (percent) at Ta.
Uz: Wind speed (m/s) at height Zw.
Rn: Net radiation, (watts/m^2). Total radiation incoming from the sky (mostly solar in daytime) less total outgoing to sky (mostly reflective in daytime) as measured with a net radiometer. If you want to include G, ground flux from soil, lump it into Rn.
Hc: Height of crop (m).
Rc: Canopy resistance (s/m).
Zw: Height of wind measurement (m), usually 2m.
Zp: Height of relative humidity and temperature measurement (m), usually 1.5m.
El: Elevation of the site above sea level (m).
Ra: Calculated air eddy diffusion resistance (s/m), not an input.

Parameters Et1	
Ta	32.48
RH	21.67
Uz	6.53
Rn	390.0
Hc	0.120
Rc	85.9
Zw	2.00
Zp	1.50
El	1609
Ra = 30.5	Uz Rn Hc Rc
Rc Method	Hc > .03
Defaults	OK Close

Rc method: Select conditions for determining canopy diffusion resistance.
   1. Force Rc value by means of direct input.
   2. Calculate Rc based on clipped grass less than .15 m high.
   3. Calculate Rc based on non-clipped grass and alfalfa, greater than .03 m high and harvested only periodically.
Defaults: Re-establishes settings in the Parameters Box if previously saved by SAVE DEFAULTS in the FILE menu.
OK: Adjusts graph and results box for current parameters.
Close: Hides the parameter box.

GRAPH BOX

Select Graph menu to open the Graph Box. Set units
and graphing modes.
  Solution Method: Direct or Combined approach to
  plotting the Penman-Monteith model on the power
  plane. They calculate the same result.
    Direct method Assumes net radiation enters leaf
      moisture as latent power, then sensible power
      and latent power must adjust adiabatically to
      keep air saturated inside the leaves.
    Combined Method plots the conventional two
      step approach. First, ignoring net radiation, air
      at the weather station level exchanges power
      adiabatically with moisture in the leaves. Then
      this display method adds net radiation as sensible heat. But moist air inside leaves
      must be saturated, so energy exchanges adiabatically to bring the point on the
      power plane back to the saturation curve. This shows explicitly how net radiation
      will divide between heat and vapor. Check Solar Lines in the Graph box to see the
      horizontal net radiation vector. This plot diagrams the two parts of the classical
      Penman- Monteith Combination Equation. Both direct and combined methods
      solve the same equations and plot the same Leaf Point. In Et-Solver there are no
      linearity assumptions for the non-linear saturation curve. (See page 11 for an
      explanation of linearity assumptions.)
  Display Q or E:
    Q: Specific humidity. Water vapor concentration, kilograms of water per kilogram of
      air-vapor mixture. (There isn't much water in even saturated air at normal
      temperatures.)
    E: Instead of Q, shows partial water vapor pressure (kPa) in the Results box.
 **Temperature Units:** Centigrade or Fahrenheit
  Et Units: Evapotranspiration in mm/hour, mm/day, inches/hour or inches/day.
  Cross hairs check box: Check if you want cross hairs on each major graph point.
  Autoscale on Parameters OK check box: Autoscale keeps the graph on the screen
    when you enter new parameters in the Parameters Box. If unchecked, you can see
    relative changes more easily.
  Defaults: Re-establishes default settings in the Graph Box. You can change defaults
    by the Save Defaults command in the File menu. To return to the original program
    defaults, delete the file et.ini in the Windows folder of your hard drive.
  OK: Enters Graph Box settings.
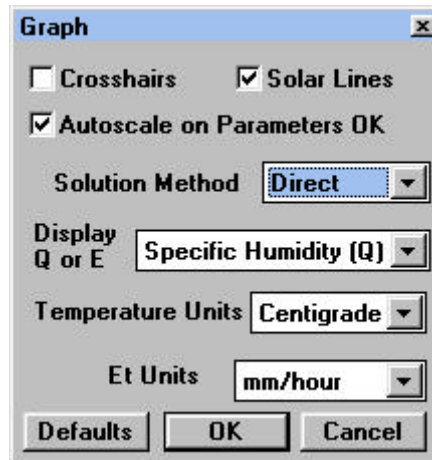
MENU ITEMS

File
  New: Creates new windows to allow running several independent models (labeled
    Et1, Et2, etc.). Click WINDOWS | Tile to display all windows.
  Close: Close window.
  Open, Save, Save As are not presently functional.

Save Defaults: You can save all the current settings in the Parameters Box and the Graph Box to the file "et.ini" in the Windows directory. These new defaults can be retrieved for the Parameters Box or the Graph Box at any time by clicking their respective Default buttons. To again use the original defaults that came with the program, delete the et.ini file. The next time you save your own defaults it will be re-created.

Print: Prints graph, results, parameter values, and units on one sheet.

Print Preview: Previews printout on the screen.

Print Setup: Enter set-up values for your printer.

View

Expand Y, Shrink Y, Auto Scale, Expand X, and Shrink X: Adjust the displayed range of the axes scales. They are all available on the TOOL BAR. Whenever Auto Scale is clicked, the program will attempt to bring your plot into the center of the display.

Clear Markers: Whenever you click your *right* mouse button, cross hairs appear at the current cursor position (click again to clear). You can create any number of these markers. They are useful for keeping track of old locations when parameters change, and for reading a graph point's location on the axes. Clear them all by clicking the Clear Markers button on the TOOL BAR.

Graph

Opens the Graph Box.

Parameters

Opens the Parameter Box.

An Explanation of the Graph Axes

Power values on the axes reference zero degrees centigrade and zero relative humidity. That is the power that would flow from a given point on the graph to a point with those zero values. For meaningful power fluxes, use cross hairs on the graph points, or markers (click right mouse button), to measure *power differences* on the scales. The Results box displays most power values of interest.

The Physical Model

Plotted vertically, differences in latent power, $Pl = \dfrac{\rho \lambda \, \Delta Q}{Ra + Rc}$, result directly in Et or dew, which is also displayed in the results box. Horizontally, differences in sensible power, $Ps = \dfrac{\rho \, Cp \, \Delta T}{Ra}$, show heat flowing between air and the canopy of leaves. If you remember the vertical axis label is really $\dfrac{\rho \lambda \, \Delta Q}{Ra + Rc}$, and the horizontal axis label is $\dfrac{\rho \, Cp \, \Delta T}{Ra}$, you can understand much about the Penman-Monteith, which is a physical model. See equations on pages 12 and 13 for definitions of terms.

A good practical reference for various evaporation models is the book, *Evapotranspiration and Irrigation Water Requirements*, American Society of Civil Engineers, Manuals and Reports on Engineering Practice No. 70 (1990). J.L.Monteith's paper, *Evaporation and Surface Temperature*, Quart. J.R. Met. Soc. (1981), 107, pp. 1-27, explains the physics and derivation of the model. Our methods for calculating Rc, Ra, and LAI (leaf area index) come from the paper *Operational Estimates of Reference Evapotranspiration*, Richard G. Allen, Marvin E. Jensen, James L. Wright, and Robert D. Burman, published in Agron. J. 81:650-662 (1989). For the basics a very readable textbook is *Principles of Environmental Physics*, Second Edition, J.L. Monteith & M.H. Unsworth.

No Saturation-Curve Linearity Assumptions in Et-Solver

   Rather than try to work with linear approximations for the non-linear saturation curve, Et-Solver uses a Newton's root-finder algorithm to find where lines intersect. The maximum error in this determination is ± 0.01 W/m² for both latent and sensible power.

   The standard Penman-Monteith combination equation finds the intersection points algebraically. It must assume straight line slopes on the saturation curve, Δ/γ^*, between points *B* and *L*, and between points *B* and the curve at *Ta* (see figure below). The combination equation first assumes that leaf temperature, *Tl*, and air temperature, *Ta*, are close enough together that the two slopes are almost the same, and they can be combined into one slope. In practice people calculate the slope at the only temperature actually measured, the air temperature, Ta, even though this slope may not be the best choice. The error is worst in highly advective conditions.

EQUATIONS

Vapor pressure $\qquad E = Es \times RH \qquad$ *where RH is relative humidity*

Saturation vapor pressure (kPa) $\qquad Es = e^{\frac{16.78T - 116.9}{T + 237.3}} \qquad$ *for $T\,°C$*

Specific humidity $\qquad Q = \dfrac{0.622E}{(P - 0.378E)}$

where

$\quad E = vapor\ pressure\,(Kpa)$

$\quad P = atmospheric\ pressure$

$\qquad = 101.3 - 0.01055 \times (elevation\ in\ meters)$

Atmospheric boundary layer resistance (s/m)

$$Ra = \frac{\ln\left(\dfrac{Zw - d}{Zom}\right)\ln\left(\dfrac{Zp - d}{Zov}\right)}{(0.41)^2\,Uz}$$

where

$\quad Uz = Wind\ Speed\,(m/s)$

$\quad Zw = height\ of\ wind\ measurement\,(m)$

$\quad Zp = height\ of\ humidity\ measurement\,(m)$

$\quad d = \dfrac{2}{3}Hc \quad displacement\ height\,(m)$

$\quad Zom = 0.123Hc \quad roughness\ length\ for\ momentum\ transfer\,(m)$

$\quad Zov = 0.0123Hc \quad roughness\ length\ for\ vapor\ and\ heat\ transfer\,(m)$

$\quad Hc = height\ of\ crop\,(m)$

Canopy resistance (s/m) $$Rc = \frac{100}{0.5\,LAI}$$

where

$LAI = leaf\ area\ index = 24Hc$
  for clipped grass less than 0.15m in height

$LAI = 5.5 + 1.5\ln(Hc)$
  for alfalfa or tall grass harvested only periodically

$Hc = crop\ height\ (m)$

Sensible power (kW) $$Ps = \frac{\rho\,Cp\,\Delta T}{Ra}$$ This is Et-Solver's horizontal axis.

where

$Cp = specific\ heat\ at\ constant\ pressure = 1.013$ $\left(\dfrac{kJ}{kg\cdot °C}\right)$

$\Delta T = temperature\ difference, °C$

Latent power (kW) $$Pl = \frac{\rho\lambda\,\Delta Q}{Ra + Rc}$$ This is Et-Solver's vertical axis.

where

$\rho = density\ of\ air\ = 1.23 - 0.112\times(elevation\ in\ meters)\times10^{-3}$ $\left(\dfrac{kg}{m^3}\right)$

$\lambda = 2.501\times10^3 - 2.361T$ $\left(\dfrac{kJ}{kg}\right)$ $T°C$

$\Delta Q = specific\ humidity\ difference$ $\left(\dfrac{kg}{kg}\right)$

For adiabatic processes $$\Delta Pl = -\Delta Ps$$

Evapotranspiration
$$Et\ = 1.4706\times10^{-3}\times Pl \quad (mm/hour)$$
where Pl is in watts

OTHER USES FOR Et-SOLVER

You can use Et-Solver to find relative humidity given wet and dry bulb temperatures. Set Solution Method in the Graph Box to Combined. Check the Crosshairs box. Set Rc Method to Forced, and set Rc = 0 to simulate a free water surface. Drag point *A* to the dry air temperature and point *B* to the wet bulb temperature. The Results box shows air and bulb temperatures. Read RH in the Parameters Box.

Solve for vapor deficit at a given Ta and RH. Vapor deficit is Es-E. Set "Display Q or E" in the Graph Box to E and check the Crosshairs box. Drag point *A* to Ta and RH (or set the values in the Parameter Box and click OK). Adjust Rn in the Parameter Box (using the Rn scroll bar, pressing OK for each new value) until the leaf point *L* is directly above the air point *A*. Read Es-E as row *L-A* column E in the Results Box.

Find Bowen Ratio: The Bowen ratio is the ratio of sensible power flux to latent power flux. In the L-A row of the Results box, Sensible power flux is Ps, and latent power flux is Pl. The Bowen ratio is typically 0.2 for a well watered crop on a sunny day. The plot shows best in direct mode with cross hairs "on".

Find canopy resistance (Rc) and air resistance (Ra). Canopy resistance is derived from an assumed leaf resistance of 100 s/m and a Leaf Area Index (LAI) that is a function of crop height and type of foliage. The two methods for calculating LAI recommended in ASCE Manual No. 70 and originating with Allen, et al. (1989) (see equations above) are available under "Rc Method" in the Parameters Box. Choose a method, adjust crop height with the Hc scroll bar (or enter Hc in its box) and see Rc displayed in its box.

Rc can also be found empirically given a known Et and known weather conditions. For this, select "Forced" in the Rc Method box and scroll Rc to get the correct Et in the Results Box, clicking OK in the Parameters Box for each change. The Et value used might come from a lysimeter or a CIMIS Et computation or simply be an assumed value.

Atmospheric boundary layer resistance to vapor and heat transport, Ra, is a function of crop height, height of the measurement point above the canopy and wind speed (see equations above). The Parameter Box allows changing these values and displays Ra. As you change wind speed (Uz, m/s) and crop height (Hc, m) with their scroll bars, Ra displays simultaneously.

Compare with CIMIS. CIMIS (California Irrigation Management Information System) runs a network of weather stations, which calculates Et with the Pruitt/Doorenbos modification of the Penman equation. The original Penman equation is simpler than the Penman-Monteith model in that leaves are considered to be always wet (Rc=0). Because of this, Et calculations generally would be too high with only air resistance (Ra). CIMIS substitutes a "wind function" for Ra. The wind function was empirically derived at the Davis, California lysimeter site. It is a linear function of wind speed. CIMIS assumes sea level elevation.