ENWATBAL.BAS: A Mechanistic Evapotranspiration Model Written in Compiled BASIC

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ABSTRACT

ENWATBAL, a mechanistic energy, water balance model originally written in the CSMP simulation language, was largely incompatible with personal computers (PCs). ENWATBAL.BAS was developed to extend the model application to PCs using BASIC which is widely available. BASIC functions or subprograms were provided to emulate CSMP language commands including integration, implicit root finding and generation of dependent variable values from tables of dependent-independent variable data pairs. The BASIC version is highly modular and thus easier to read and maintain. The verification of ENWATBAL.BAS against ENWATBAL, using identical input data, discretization and time integration steps, indicated no appreciable differences between the two versions. Runtimes for a seasonal simulation (100 days) were nearly the same (about 5 hours) for the compiled BASIC version using a 20 MHz, 80386 based PC and the CSMP version using a MicroVAX II, and four times faster for a 33 MHz, 80486 based PC. Discretization analysis showed that soil layer thickness should be no larger than 0.002 m for the surface layer although thickness may increase to as much as 0.2 m for subsurface layers. Parameter sensitivity analysis showed that evapotranspiration estimates changed as expected in response to changes in parameter values for surface roughness length, maximum crop water potential, soil albedo, and crop hydraulic resistance. Many model changes were made to the BASIC version subsequent to the speed comparisons resulting in a more advanced and flexible model. ENWATBAL.BAS is a useful tool for investigating the complex mechanisms of evapotranspiration.

Simulation models are useful tools for investigating questions which are difficult to examine via field studies, for designing better field experiments, and for gaining insight into how the parts of a complex system interact. ENWATBAL (Energy and Water Balance), a mechanistic evapotranspiration (ET) model, was originally written in the CSMP simulation language (Continuous System Modeling Program, e.g., Speckhart and Green, 1976). It was used to predict cotton ET (Lascano et al., 1987) and sorghum ET (Van Bavel and Lascano, 1987) at Lubbock, TX. More recently Ritchie and Johnson (1990) compared ENWATBAL to the functional CERES-Maize model for predicting sorghum ET. Krieg and Lascano (1990) used ENWATBAL to predict sorghum ET at Brownfield, TX, and Lascano (1991) used the model to predict the effects of N on the water use of irrigated and dryland sorghum at Lubbock, TX.

The main purpose of ENWATBAL is the separate calculation of soil and crop evaporation as a function of crop development and weather via numerical modeling of the energy and water balances of the soil - plant - atmosphere system. ENWATBAL is not a crop growth and development model; however, because it predicts soil water content and temperature, it can be used to investigate agronomic implications, such as seedling emergence, irrigation strategies, and other processes depending upon soil water and temperature. The primary purpose of this work was to rewrite ENWATBAL to execute in a computer language which is more accessible, more flexible and more widely used than CSMP. Therefore, ENWATBAL.BAS was developed to extend the model application to personal computers (PCs) using the BASIC language.

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Abbreviations: ASCII, American Standard Code for Information Interchange; CPU, central processing unit; CSMP, Continuous System Modeling Program; DOS, disk operating system; ET, evapotranspiration; LAI, leaf area index; and PC, personal computer.

Our objectives were, i) port ENWATBAL to the IBM[1] ® PC/AT compatible family of computers, ii) compare performance of ENWATBAL on a MicroVAX II and a PC, iii) make enhancements and corrections to the model, and iv) examine the enhanced model's performance including parameter sensitivity analysis and discretization analysis neither of which had been previously performed for ENWATBAL.

MODEL DESCRIPTION

ENWATBAL is a one-dimensional numerical, dynamic model of the energy and water balances of the soil-plant-atmosphere continuum. The soil is divided into several layers (finite differences) with typically thinner layers close to the surface. The crop canopy, if it exists, is defined as a single layer (big leaf model) with no thickness and therefore no water storage. The atmosphere is defined as a source/sink with known temperature and water vapor pressure. Fluxes of energy and water are represented as rate equations which are integrated at each time step. Fluxes of water and energy between the soil and atmosphere are calculated separately from those between the canopy and atmosphere. Therefore if no crop exists the model will calculate evaporation from bare soil. For bare soil the model is similar to the CONSERVB model (Lascano and Van Bavel, 1986). Van Bavel and Lascano (1987) give a flow chart of the ENWATBAL model processes and a listing of the CSMP code, and discuss the equations solved by the model. A brief description is given here with key energy balance equations given in the Appendix. For ease of reference to the program, variable names are those used in the program code. Variable arrays are denoted by subscripted numbers with the number corresponding to the variable position in the array.

Soil water flux including infiltration is calculated using Darcy's law. The lower soil boundary condition can be defined as a rate equal to the unit gradient rate for flux at the current (for each time step) soil water potential; or, flux can be set equal to zero. The latter option is useful for evaluating flux in closed lysimeters. For rainfall rates less than the infiltration capacity of the top soil layer (and if no previously ponded water exists) the upper boundary condition for water flux is the rainfall rate, otherwise the upper boundary condition is the depth of ponding calculated as the cumulative difference between infiltration rate and rainfall rate. The infiltration capacity of the soil, INCAP (m s^{-1}), is calculated as:

$$INCAP = - HPOT_1 \cdot [(SATCON + COND_1)/2]\ DIST_1 \quad [1]$$

where $HPOT_1$ is the soil water potential of the top soil layer (m), SATCON is the saturated hydraulic conductivity of the top soil layer (m s^{-1}), $COND_1$ is the hydraulic conductivity (m s^{-1}) of the top soil layer at the current soil water potential, and $DIST_1$ is the distance from the surface to the middle of the top soil layer (m).

Soil heat flux is calculated using Fourier's law with thermal conductivity corrected for heat transport by vapor flux. The lower soil boundary condition for heat flux is a constant temperature equal to that given given by the user for the lower boundary in the initial soil water and temperature profile. The upper boundary condition for soil heat flux, including latent heat flux, is defined implicitly by the set of equations describing the surface energy balance. This set of equations is arranged so as to define surface temperature, T_s, and solved for T_s with an implicit root finding algorithm (Appendix, Function IMPL3). The upper boundary condition for the canopy is likewise defined implicitly by the set of equations describing the canopy temperature, T_c, in terms of the energy balance, and which are solved for T_c (Appendix, Function IMPL2). For both soil and canopy the solution of the energy and water balance equations defines the latent heat flux, sensible heat flux and long wave radiation flux. In addition the canopy water potential is found as the root of the implicit set of equations describing the transpiration rate as a function of epidermal conductance which is itself dependent on canopy water potential (Appendix, Function IMPL1).

Since ENWATBAL is not a crop growth model it requires daily input data on leaf area index, depth of rooting and depth of maximum root length density. The LAI value is used in polynomial functions describing turbulent resistance between the canopy and air and between the soil and air; and, in polynomial functions describing the optical properties (transmittance and absorptance) of the canopy and soil surface, as suggested by Chen (1984). The LAI value is also used in the equation describing root water uptake which is assumed proportional to LAI (plus other factors). The rooting parameters define a triangular rooting pattern which is converted to a fractional root density for each soil layer normalized to unity for the entire root zone. The fractional root density is used to calculate an effective soil water potential for the root zone; and, to limit the rate of root water uptake from a given layer.

[1] Trade names and company names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the USDA or Texas A&M University.

DATA REQUIREMENTS

Input data files for ENWATBAL.BAS are listed in Table 1. The model may be run with either half-hourly or daily input data but accuracy is substantially improved if half-hourly data are used. If daily data are used the data requirements are: day of year, maximum and minimum air temperature (C), maximum and minimum dew point temperature (C), and mean wind speed (m s^{-1}), all measured at 2 m height; total solar radiation (MJ m^{-2}), leaf area index, rooting depth (m) and depth of maximum root length density (m). These are contained in file ENWATBAL.XX where XX represents the last two digits of the year. Precipitation and irrigation input data are contained in a separate file (IRR-PREC.XX). The day of year and number of events in that day are specified on one line, and beginning and ending times (decimal hour) and depth (mm) of each event are given on separate lines. If only daily totals of precipitation and irrigation are available then the lumped depth value may be assigned to a reasonable beginning time and duration but accuracy of daily evapotranspiration predictions is greatly improved if actual times and depths are used.

If half-hourly input data are to be used then the leaf area index, rooting depth and depth of maximum root length density (m) values are still needed on a daily basis but the other values may be replaced by zeros in the file ENWATBAL.XX. File IRR-PREC.XX is still needed. Half-hourly data are found in file WP.DAT and include: day of year, wind speed (m s^{-1}), air temperature (C) and dew point temperature (C), all measured at 2 m height; and solar radiation (MJ m^{-2}) and barometric pressure (kPa). Half-hourly data are assumed to be means with the first mean centered around 15 minutes after midnight. Each line represents a half-hour increase in time.

In addition to the weather and plant growth data described above the model requires initial conditions and tabular descriptions of several functional relationships. Initial conditions for the soil profile are contained in the file INIT.XXX where XXX is the day of year when the simulation is to begin. This day of year value is used to find the appropriate starting day in files ENWATBAL.XX, IRR-PREC.XX and WP.DAT. For each layer, used in the finite difference solutions for soil water and heat fluxes, file INIT.XXX contains layer thickness (m), volumetric soil water content, temperature (C) and horizon number. The horizon number begins with 1 for the top horizon and increments one for each horizon having different soil water characteristic curves. There are usually several soil layers in each horizon. Other initial conditions are contained in file ENWATBAL.CON. These include the surface roughness length (m), maximum crop water potential (m), specific hydraulic resistance of the crop (s), ponded water detention capacity (m), latitude (degrees), mean barometric pressure (kPa), and upper and lower time step limits (s).

Tabular descriptions of functional relationships are contained in the file ENWATBAL.FGN. Data are arranged in pairs, one data pair to each line. Relationships include: leaf water potential (m) vs. epidermal conductance (m s^{-1}), solar radiation (W m^{-2}) vs. epidermal conductance (m s^{-1}), soil temperature (C) vs. heat conductivity by vapor (W m^{-1} C^{-1}), and volumetric water content vs. soil albedo. For each soil horizon, relationships of volumetric water content vs. soil water potential (m); and, vs. hydraulic conductivity (m s^{-1}) are included. Since the model will simulate drying of the top soil layer to very near air dryness these soil water characteristic relationships must include values of water content lower than the expected air dry value.

PORTING

When porting a research computer code from one CPU environment to another it is desirable to use a language which is commercially available and popular so that other users may easily read, modify and run the program. In this way the code can be modified, expanded and used by others, thus reaching its maximum effectiveness as a research tool. The CSMP language is no longer supported by IBM. Also, CSMP, while providing a range of optional methods for integration of differential equations, makes it difficult for the user to modify existing methods or include new ones. The user is similarly limited in choice of implicit equation solvers and ability to modify what is available in CSMP. Finally, since CSMP is built around the concept of integrating differential equations to solve systems of equations describing physical systems, it has limited potential for implementing the many efficient finite difference solutions now available (e.g. Ross, 1990). In short, CSMP has been largely surpassed by advances in numerical methods, and the availability of personal computers and scientist programmers willing and able to use them. Therefore, we chose not to use the CSMP simulation language even though a PC version is available.

Besides being widely available, a language for porting computer code should allow modular structure for ease of writing and reading the code and should offer both user defined functions and callable subprograms. User defined functions are particularly important since they allow the programmer to recreate functions available in the language of the original code and thus avoid some complicated rewrites of complex algorithms. A powerful and fast editing and debugging environment is important to reduce porting time. Also, the language should allow compilation of the completed code to obtain execution speeds comparable to those obtained by other compiled languages such as FORTRAN.

Many languages provide some of these features but the modern BASIC languages are perhaps unique in being both widely understood by research scientists and providing those features which reduce porting time while still producing fast executable code. BASIC is also structurally and mnemonically similar to FORTRAN thus simplifying this particular porting effort. FORTRAN and BASIC are much more similar than, for instance, FORTRAN and C or Pascal. Microsoft ® BASIC was chosen as the target language because of the senior author's previous successful experience with it in writing simulation models and because it provided all the desired features.

Table 1. Input data file system for ENWATBAL.BAS.

Name	Description
ENWATBAL.FIL[†]	Must follow the program name on the DOS command line.Contains names of the five data files with appropriate drive and path information for each, e.g., "D:\DATA88\INIT.173". Also has day of year to end simulation, path for output files and redirection instructions.
INIT.173	Contains initial soil profile data including thickness, water content and temperature for each layer. The file name extension is a number indicating the day of year on which to start the simulation.
IRR-PREC.88	Contains depth and duration data for irrigation and precipitation events for each day.
ENWATBAL.88	Contains daily means of other weather data and plant growth data. The file name extension is 2 numbers giving the year in which the data starts.
ENWATBAL.CON	Contains parameter values that may change from one run to another.
ENWATBAL.FGN	Contains data tables for function AFGEN.
WP.DAT	Contains half-hourly means of weather variables.

[†]ENWATBAL.BAS is run with a DOS command line of the form:
ENWATBAL ENWATBAL.FIL <CR>
where <CR> denotes pressing the enter (return) key and ENWATBAL.FIL is the name of a file containing the names of the five data files required by ENWATBAL.BAS. The names of ENWATBAL.FIL and of the data files may be changed by the user.

Function Porting

The CSMP language offers several simulation functions not available in BASIC. Three of the functions most commonly used in numerical analysis involve integration of differential terms, solution of implicit sets of equations, and generation of dependent variable values from tables of dependent-independent variable pairs. These were used in ENWATBAL and were replicated when the code was ported to ENWATBAL.BAS (Table 2). Since a great deal of existing simulation code has been written in CSMP (e.g. Hillel, 1977; Goudriaan, 1977) we discuss the porting of these functions and will make the code available to others who desire to port CSMP programs.

The integration subprogram, INTGRL, was replicated using a simple rectangular integration method. While in CSMP several integration techniques are available including some variable time step routines, ENWATBAL has been successfully used with the rectangular integration option (Lascano et al., 1987). Rectangular integration is by far the simplest to code. To improve efficiency while reducing errors, we introduced a variable time step algorithm which is independent of the integration function. Since ENWATBAL.BAS is modular a more sophisticated integration routine can be included in the future with minimal changes in code outside of the routine.

The function generator, AFGEN, was replicated with BASIC code. AFGEN is an arbitrary function generator which linearly interpolates between values of a dependent variable, Y, given a value of an independent variable, X, and a table of X and Y data pairs. AFGEN is used at each time step to return values of several functions inherent to a mechanistic water and heat flow model for the soil-plant-atmosphere continuum. These include hydraulic conductivity and soil water potential as functions of soil water content, heat conductivity by vapor as a function of soil temperature, epidermal conductance as a function of leaf water potential and of solar radiation, and soil aldebo as a function of water content.

The CSMP implicit equation solver, IMPL, was replaced with a user defined function, IMPLx, derived from an implicit equation solver given by Press et al. (1986, p. 253). This solver finds the root of an implicit set of equations by a combination of root bracketing, bisection and inverse quadratic interpolation. The implicit equation solver is essential since leaf temperature, leaf water potential and transpiration rate, and soil surface temperature and evaporation rate are each represented by implicit sets of equations in the model. The solver was modified to replace function calls to the three sets of implicit equations with inline code. Thus, the x in IMPLx is a number corresponding to one of these implicit sets of equations, i.e., we actually have IMPL1, IMPL2 and IMPL3. The solver was also changed to reverse the sign of one of the bracket values and try again if failure occurred. This modification allowed the other bracket value to be close to the root with consequent quick solutions while avoiding the risk of failure that would occur if both supposed bracket values were on the same side of the root. Also, for ease of porting, the FORTRAN functions SIGN, AMIN, ARSIN and ARCOS, which do not have equivalents in BASIC, were reproduced with BASIC user defined functions.

Code Changes and Enhancements

With 11 user defined functions and 16 subprograms, ENWATBAL.BAS is highly modular and thus easy to read, debug and, most importantly, to modify. Several algorithmic enhancements were made after the porting and the comparisons of MicroVAX II to PC performance were completed. The surface hydrology code was revised to include calculation of dewfall. Root uptake was corrected to equal transpiration. The precipitation generation code was rewritten to allow multiple precipitation events on a single day. A variable time step algorithm was included which is sensitive to conditions which may cause divergence of the solution. Code was added to allow the use of weather data collected on a half-hourly basis as well as the daily weather data originally used. Also, new code allows up to nine soil horizons with different hydraulic properties.

An algorithm was written to allow the constant value of soil albedo to be varied for each run by the user. This was necessary for the albedo parameter sensitivity analysis. This algorithm was later extended to allow soil albedo to vary as a function of surface soil water content. Idso et al. (1974) found several different curvilinear relationships between albedo and surface soil layer volumetric water content for different surface layer thicknesses varying between 0.002 m and 0.01 m. The user can define the dependence of albedo on surface layer water content in a table of values which are used internally by the AFGEN function to calculate albedo.

Several ease of use enhancements were made. The user can interrupt execution on any day by pressing the "Escape" key, and restart where the simulation left off by simply typing "RESTART" and pressing the "Enter" key at the DOS prompt. Hourly values of 35 important variables may be output in a format suitable for plotting. All input data are read from ASCII files (Table 1), allowing the user to make runs with different sets of data and parameter values without changing and recompiling the program code. The program can be run from a batch file, which fact allows multiple unattended runs with different data sets.

Error Trapping and Debugging

Numerical errors occur when the solution of the flow equations diverges. ENWATBAL had no error trapping nor explicit debugging features. In ENWATBAL.BAS divergence usually causes the implicit root finding function, IMPLx, to fail because either the leaf temperature, soil surface temperature or plant water potential go beyond the range bracketed by *LLim* and *HLim*. Such an error is trapped and the values of 11 important variables over the last 20 time steps are stored in a file (Table 3) for debugging purposes. The file also contains final cumulative values of all integrated variables, and final values of several layer-related variables for each soil layer.

Checking and reporting of errors in data file input was also implemented. In most cases this is limited to checking for valid data file names and the existence of the file; and, to checking for the correct number of variables and proper incrementing of the day of year value in each file.

Table 2. Continous System Modeling Program (CSMP) and FORTRAN functions and statements that were used in the CSMP version of ENWATBAL, but were not available in BASIC, were rewritten as BASIC functions and subprograms.

Name	Description
INTGRL(*Y*,*dY/dt*)	A rectangular integration subprogram where *dY/dt* is the rate of change and *Y* is the integral value returned.
AFGEN(Table(),*X*)	A function. The value of AFGEN is a linearly inter-polated value of *Y* corresponding to the value of *X*. The argument Table() is an array of *X* and *Y* data pairs.
IMPLx(*LLim*,*HLim*,*Tol*)	Actually three separate functions, IMPL1, IMPL2 and IMPL3. The value of each function is the root of an implicit set of equations in *Y*. The x in IMPLx is a number corresponding to one of the three implicit sets of equations solved in ENWATBAL, *LLim* and *HLim* are the lower and upper bounds of *Y* bracketing the solution, and *Tol* is the error tolerance to which the root is determined.
SIGN(*X1*,*X2*)	A function which has the absolute value of *X1* with the sign of *X2*.
AMIN(*X1*,*X2*)	A function which has the value of *X1* or *X2* whichever is least.
ARSIN(*X*)	A function which is the inverse sine of *X*.
ARCOS(*X*)	A function which is the inverse cosine of *X*.

MICROVAX II AND PC RESULTS COMPARED

The CSMP version of ENWATBAL was run on a MicroVAX II and the ported version (ENWATBAL.BAS without enhancements) was run on a DELL model 310 with an 80386 CPU running at 20 MHz and a 80387 math coprocessor, and on a CLUB American model Eagle 400 with an 80486 CPU running at 33 MHz. The latter two machines are IBM PC/AT compatible. The

Table 3. Names and descriptions of the program variable values that are written to file ENWATBAL.PRN, when a fatal error in execution of ENWATBAL.BAS occurs, as an aid in finding the reason for failure.

Name	Description
TA	Air temperature, °C
DPTC	Dew point temperature, °C
TL	Leaf temperature, °C
WPCR	Canopy water potential, m
HL	Leaf substomatal humidity, kg m^{-3}
$TEMP_1$	Temperature of the top most soil layer, °C
$KOND_1$	Thermal conductivity of the top most soil layer, J s^{-1} m^{-1} $°C^{-1}$
TS	Soil surface temperature, °C
$PPOT_1$	Soil water potential in the top most soil layer, m
$THETA_1$	Soil water content in the top most soil layer, m

PC version was run under Microsoft DOS version 3.3. A common input data set, from a 102 day sorghum crop grown at Bushland, TX in 1988 (Howell et al., 1990), was used to compare model output and run times in a realistic fashion. Only daily mean and maximum and minimum input values were used. Rectangular integration was used and discretization and time steps were identical for all runs. Output was curtailed in ENWATBAL.BAS to duplicate that available from ENWATBAL. Key parameter values were Z_o = 0.01 m, WPCRMX = -10 m, α = 0.175 and SRCR = 1 x 10^9 s for the comparison runs (see next section for parameter explanation). Thickness of the top soil layer was 0.005 m.

Runtimes were nearly the same, about 5 hours, for the MicroVAX II and the 80386 based PC. The 80486 based PC was four times faster, finishing in little over an hour. Predicted evaporation, transpiration and evapotranspiration (ET) were practically identical, with the slight differences probably due to the provision for dew fall in ENWATBAL.BAS (Figures 1 and 2). There were no differences in results from the 80386 and 80486 based PCs. Water balance error was less than 2% of cumulative ET, a reasonable value.

PARAMETER SENSITIVITY ANALYSIS

The model's sensitivity to four parameters was tested. These were the surface roughness length, Z_o [m]; the maximum crop water potential, WPCRMX [m]; the soil reflectance to shortwave radiation, α; and the crop hydraulic resistance, SRCR [s]. Changes in soil evaporation calculations may affect results for transpiration and vice versa since such changes affect soil water potential values used in both sets of calculations. Therefore cumulative predicted values, for the season, of evaporation from the soil surface, transpiration and ET were used as evaluation criteria. The predicted values were normalized by dividing by the lysimeter measured value of cumulative ET, which was 390 mm over the same period. Since water balance errors were less than 2% and drainage amounts were minor any differences in ET were accounted for by changes in soil moisture storage.

ENWATBAL is a numerical model which treats the plant canopy as a single layer and the soil as multi-layered. Evaporation from the soil and transpiration from the plant are calculated separately from energy balances and transfer resistances at the soil surface and the canopy (Lascano et al., 1987). In both cases the transfer resistance is calculated as a function of leaf area index,

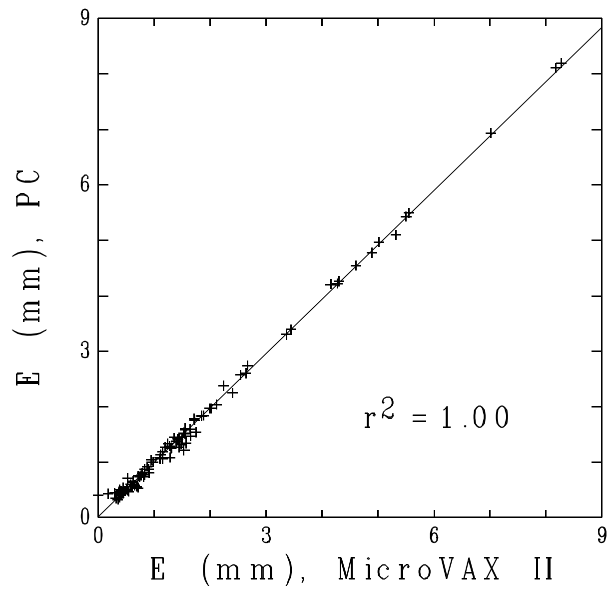

Figure 1. Comparison of daily values of evaporation computed by ENWATBAL on a MicroVAX II and on a PC. Key parameter values were Z_o = 0.01 m, WPCRMX = -10 m, α = 0.175 and SRCR = 1 x 10^9 s.

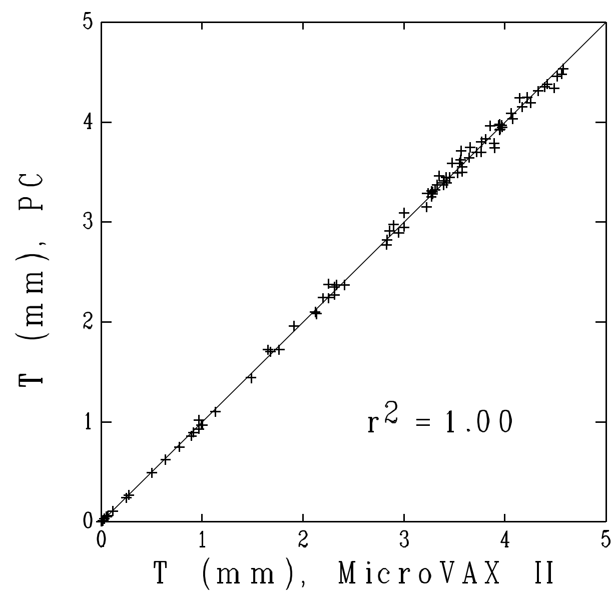

Figure 2. Comparison of daily values of transpiration computed by ENWATBAL on a MicroVAX II and on a PC. Key parameter values were Z_o = 0.01 m, WPCRMX = -10 m, α = 0.175 and SRCR = 1 x 10^9 s.

LAI [$m^2\ m^{-2}$], and the bare soil aerodynamic resistance, r_a [$s\ m^{-1}$], which we simplified as:

$$r_a = [\ln(Z/Z_o)]^2/(0.16\ U) \qquad [2]$$

where Z is the height [m] at which the wind speed, U [m/s], is measured and Z_o is the surface roughness length [m]. The value of Z_o has a potentially large effect on evaporation and transpiration estimates. An empirical relationship for Z_o is (Campbell, 1977, Eq. 4.12 & 4.13):

$$Z_o = 0.026\ h \qquad [3]$$

where h is the height of the surface roughness elements [m]. For a furrow and bed system the value of h may be close to 0.15 m so Z_o may be about 0.004 m. For parameter sensitivity analysis we varied Z_o from 0.0001 to 0.05 m. As the value of Z_o decreased evaporation was reduced greatly but transpiration was only slightly affected (Figure 3). This was appropriate since transpiration is affected by crop height as well as the surface roughness length. Cumulative ET was reduced monotonically as expected.

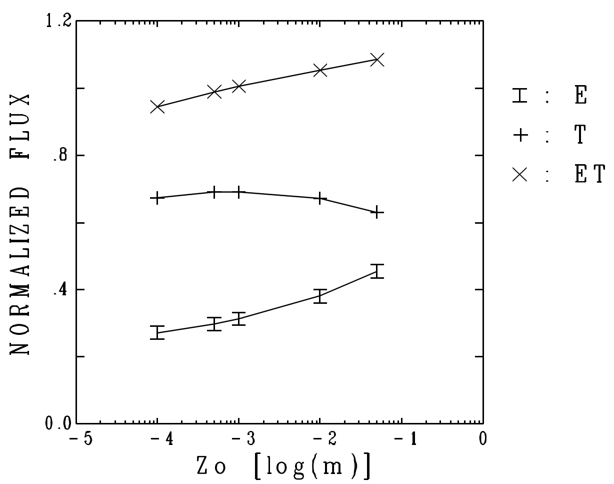

Figure 3. Roughness length (Z_o) effect on seasonal evaporation (E), transpiration (T) and evapotranspiration (ET). Key parameter values were WPCRMX = 0 m, α = 0.5 and SRCR = 1 x 10^9 s. Normalized by dividing by measured seasonal ET.

Albedo is the fraction of short wave radiation reflected from a surface. The value of soil albedo, α, will strongly affect the energy balance at the soil surface and thus evaporation from the soil surface. The short wave radiation balance under a crop canopy is also affected by the amount of radiation transmitted by the canopy. In ENWATBAL the combined effects of soil albedo and canopy transmittance of short wave radiation were represented by a polynomial function of leaf area index (LAI):

$$\begin{aligned} ABSS = (1 - \alpha) - 0.6447\ LAI + 0.2646\ LAI^2 \\ - 0.05695\ LAI^3 + 0.005937\ LAI^4 \\ - 0.0002355\ LAI^5 \end{aligned} \qquad [4]$$

where α was fixed at 0.175. The parameter ABSS, the shortwave absorptance of the soil, was multiplied by global solar radiation to give the net shortwave radiation at the soil surface. Details of the derivation of Equation 4 are given in Van Bavel and Lascano (1987). To perform parameter sensitivity analysis using albedo we scaled the ABSS function for other albedo values using:

$$ABSS_\alpha = ABSS\ (1 - \alpha)/0.825 \qquad [5]$$

The new absorptance parameter, $ABSS_\alpha$, was then multiplied by global solar radiation to give the net shortwave radiation at the soil surface. Equation 5 gave the family of curves shown in Figure 4. These curves are realistic in so far as the albedo is exactly reproduced when LAI is zero, and the effect of albedo is minimal for high LAI values. Soil albedo may vary between 0.02 for dark wet clay and 0.50 for dry salt covered soil (Van Wijk and Scholte Ubing, 1963). We used albedo values ranging from 0.1 to 0.5 for parameter sensitivity analysis. Increasing soil albedo decreases the energy available for evaporation from the soil. As expected, estimated evaporation decreased as α increased but transpiration increased along with α due to higher soil water contents (Figure 5). Although the net effect on ET was small, evaporation was decreased by 11%. In ENWATBAL albedo was held constant over the day and throughout the season.

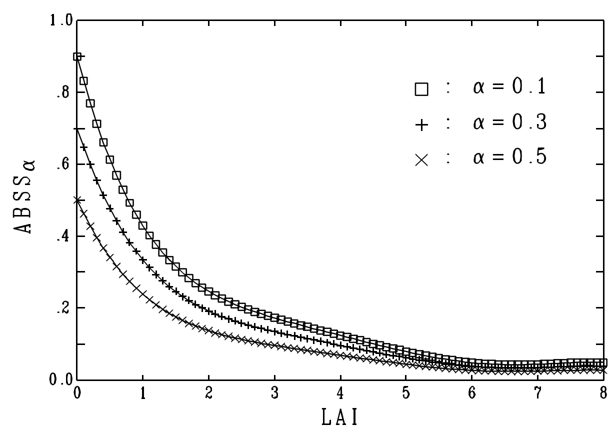

Figure 4. Soil surface shortwave radiation parameter, ABSS, as scaled for three different soil albedos giving $ABSS_\alpha$.

Idso et al. (1974) have shown that albedo may change by as much as 0.12 in a few hours as the soil surface dries. They also showed that, for a 0.002 m thick surface layer, the relationship between albedo and volumetric water content was linear. Since ENWATBAL can use an arbitrarily thin surface layer such a linear relationship could be applied. Our parameter sensitivity results showed that the linear relationship should be applied if the partitioning of ET into E and T is of interest. In the version of ENWATBAL.BAS now available we use the AFGEN function to generate albedo as a function of top layer water content prior to scaling ABSS to $ABSS_\alpha$ using Equation 5.

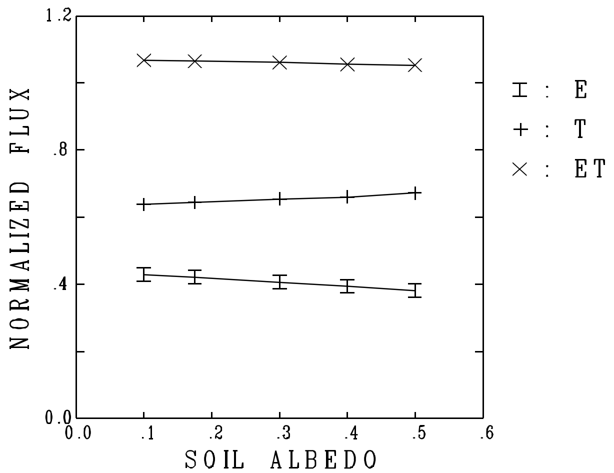

Figure 5. Soil albedo effect on seasonal evaporation (E), transpiration (T) and evapotranspiration (ET). Key parameter values were Z_o = 0.01 m, WPCRMX = 0 m and SRCR = 1 x 10^9 s. Normalized by dividing by measured seasonal ET.

Transpiration is partitioned over the multiple soil layers of the root zone according to:

$$RC_i = \frac{(WPOTCR - WPCRMX - PPOT_i)}{RF_i\ LAI/SRCR} \qquad [6]$$

where RC_i is the root water uptake [m/s] in layer i, WPOTCR is the canopy water potential [m], WPCRMX is the maximum observed canopy water potential [m], $PPOT_i$ is the soil water potential [m] in layer i, RF_i is the fractional root density [dimensionless] in layer i, LAI is the leaf area index, and SRCR is the crop specific hydraulic resistance [s]. The LAI term enters into Equation 6 because SRCR is a resistance per unit LAI. Obviously, the value chosen for SRCR will have a large effect on transpiration estimates. Reicosky and Ritchie (1976) estimated SRCR = 1 x 10^9 s for well watered field sorghum. Van Bavel and Ahmed (1976) used SRCR = 1.1 x 10^9 s for sorghum. Kirkham (1988) found SRCR for drought resistant and drought sensitive sorghum varieties to be not significantly different from 3.5 x 10^9 s in a growth room under well watered conditions. Thus, the value of 1 x 10^9 s used for SRCR by Van Bavel and Lascano (1987) for sorghum seems appropriate.

We varied SRCR from 1 x 10^8 to 1 x 10^{10} s for parameter sensitivity analysis. As SRCR was increased the expected decrease in transpiration and ET occurred (Figure 6). However, the expected increase in evaporation, as transpiration decreased, did not occur. This problem was traced to an incorrect routine for root uptake of soil moisture which could cause water balance errors in the CSMP version of ENWATBAL. For each order of magnitude increase in SRCR the water balance error increased by a factor of 5. This problem did not affect the results from the other parameter sensitivity analyses since SRCR remained constant for each analysis. The root uptake algorithm was corrected in the version of ENWATBAL.BAS now available, reducing water balance errors to less than 1 mm over the season. The strong sensitivity of transpiration to crop hydraulic resistance suggests that SRCR should not be a constant in the model. This is supported by known sensitivity of SRCR to temperature, growth stage and xylem water potential (Ameglio et al., 1990; Radin, 1990; Kramer, 1983).

We note here that root water uptake in this model is not directly influenced by soil hydraulic resistance as, in theory, it should be. Neither is uptake dependent upon position of the soil layer where uptake occurs except for the slight influence of gravitational (elevation dependent) soil water potential changes. Reid and Huck (1990) have presented a model which incorporates resistance changes dependent on the differing length of roots involved in uptake when the surface soil dries and the plant must take up water from deeper layers. Their modeling results showed diurnal variations in crop hydraulic resistance similar to those observed by others (e.g. Kramer, 1983). A similar algorithm is being considered for future versions of ENWATBAL.BAS

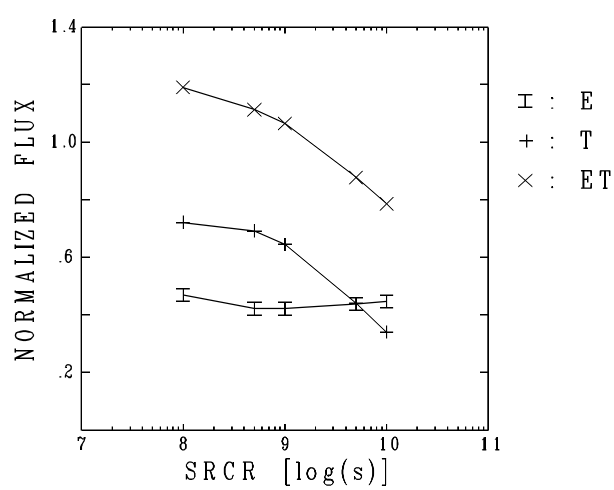

Figure 6. Crop hydraulic resistance (SRCR) effect on evaporation (E), transpiration (T) and evapotranspiration (ET). Key parameter values were Z_o = 0.01 m, WPCRMX = 0 m and α = 0.175. Normalized by dividing by measured seasonal ET.

The maximum observed canopy water potential, WPCRMX, is the value that would be measured for a well watered crop early in the morning. The value of WPCRMX affects the hydraulic gradient and thus transpiration estimates. Kirkham (1988) found well watered sorghum leaf water potential measured at about 10 AM daily to vary between -10 and -20 m. Reicosky and Ritchie (1976) found well watered sorghum leaf water potential to vary from about -35 to -150 m between 6 AM and 1 PM in the field. Again Van Bavel and Lascano's (1987) value of -10 m for WPCRMX is appropriate. For parameter sensitivity analysis we used WPCRMX values between 0 and -20 m.

As WPCRMX was decreased cumulative transpiration decreased as expected (Figure 7). Evaporation increased slightly over the same range due to higher soil water contents but the overall effect of reducing WPCRMX was to reduce cumulative ET. There was not a strong effect on ET. Since the highest r^2 value for regression of daily predicted vs. lysimeter measured ET was for WPCRMX = 0, that value was used for other runs.

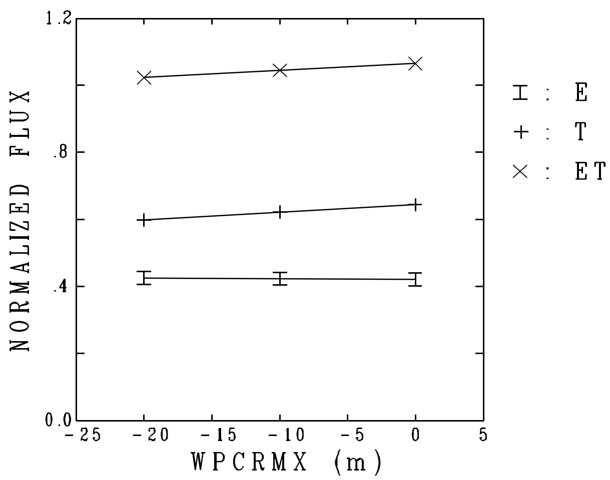

Figure 7. Effect of maximum crop water potential (WPCRMX) on seasonal evaporation (E), transpiration (T) and evapotranspiration (ET). Key parameter values were Z_o = 0.01 m, α = 0.175 and SRCR = 1 x 10^9 s. Normalized by dividing by measured seasonal ET.

DISCRETIZATION ANALYSIS

Energy must be partitioned between soil heat flux, sensible heat flux and evaporation from the soil surface to complete the surface energy balance which is only partly determined by soil albedo and short wave radiation partitioning at the surface. Energy partitioning was accomplished by implicitly solving for the soil surface temperature which simultaneously satisfies the equations for sensible heat flux, latent heat flux, soil heat flux, and emission of long wave radiation. The latent heat flux is determined by the gradient, between the absolute humidity at the soil surface and that of the air at reference height, multiplied by the transfer coefficient. However the soil's absolute humidity cannot be given at the surface and so is calculated as an average value for the top soil layer. This may lead to overestimation of latent heat flux if the layer thickness is too large since the absolute humidity deeper in the soil will usually be larger than that at the surface. For their model of evaporation from bare soil, CONSERVB, Lascano and Van Bavel (1986) found that the top layer thickness should be no larger than 0.005 m. Reynolds and Walker (1984) found that layer thickness near the surface should not be greater than 0.002 m for simulation of evaporation from soil cores. We used first layer thicknesses ranging from 0.01 to 0.001 m in our discretization analysis.

As the thickness of the uppermost soil layer was decreased from 0.01 to 0.001 m the value of cumulative evaporation decreased by 14.7% while transpiration increased by 9.3% (Table 4). But seasonal ET changed by less than 1%. Lascano and Van Bavel (1986) found a similar effect with CONSERVB, a model of evaporation from bare soil and a precursor to ENWATBAL. However, they found only a 4.5% reduction in evaporation as layer thickness decreased from 0.005 to 0.001 m compared to our 8.5% reduction over the same range. This difference may be due to an order of magnitude difference in the hydraulic conductivity data used in the two simulations. The relatively small dependence of cumulative ET estimates on layer thickness suggests that, if partitioning of ET into evaporation and transpiration is not important, then a thicker top soil layer may be acceptable. This is an important distinction because run times doubled as top layer thickness decreased from 0.01 to 0.001 m.

Table 4. Effect of top soil layer thickness on cumulative evapotranspiration normalized by dividing by measured seasonal ET. Key parameter values were Z_o= 0.01 m, α = 0.175 and SRCR = 1 x 10^9 s. These runs were done after the root uptake algorithm was corrected.

Layer Thickness [m]	Normalized Evaporation	Normalized Transpiration	Normalized ET
0.001	0.406	0.712	1.118
0.002	0.408	0.705	1.113
0.004	0.439	0.685	1.124
0.005	0.443	0.681	1.125
0.006	0.448	0.677	1.125
0.008	0.462	0.664	1.126
0.010	0.475	0.652	1.127

SPECIFICATIONS, DOCUMENTATION, AND AVAILABILITY

The program has been run under Microsoft DOS (MSDOS) versions 3.3 through 5.0 and Digital Research DOS (DRDOS) version 6.0 on IBM PC/AT compatible computers with at least 512 kilobytes of memory. The executable code may be run without benefit of a compiler or interpreter but implementation of changes to the source code made by the user will require either of two compilers sold by Microsoft, QuickBASIC version 4.5 or Professional BASIC version 7.X. For data sets of more than a few days a fast computer (e.g. Intel 80486 at 33 MHz) with several Mbytes of memory is recommended. The program, source code and 100 days of daily data require about 1.2 Mbytes of disk storage space. A half-hourly input data set for 100 days requires about 700 kbytes of disk space. A hard disk is essential for any but the most trivial data sets. If hourly output is specified a RAM disk on the order of 1 to 4 Mbytes is recommended in order to speed up writing of data to files. In order to create data files the user will need an ASCII (text) editor or a spreadsheet or database capable of creating ASCII data files.

The BASIC source code is heavily commented including descriptions of variables and their units and descriptions of the workings of each section of code. A user's guide and documentation of input and output file formats including description of each variable and its units are available in printed form. Requests for source and executable code and documentation should be addressed to the first author at USDA-ARS, P.O. Drawer 10, Bushland, TX 79012. Documentation for the CSMP version has a more thorough discussion of the algorithms than is currently available for the BASIC version. The CSMP version and documentation may be obtained from the second author at Texas A&M University, Agricultural Research and Extension Center, Rt. 3, Box 219, Lubbock, TX 79401-9757.

SUMMARY

ENWATBAL was successfully ported to the IBM PC/AT environment where runtimes were shorter than those on a MicroVAX II minicomputer. However, the enhanced version (half-hourly input data, output of 35 variables on an hourly basis, corrected root water uptake, etc.) runs considerably slower. Further speed increases are obtainable if the algorithms for heat and water flow in the soil are recast in a more efficient finite difference form. Parameter sensitivity analysis showed that the model responded as expected to changes in values of the aerodynamic roughness length, maximum crop water potential and soil albedo. ET response to changes in crop hydraulic resistance (SRCR) was not entirely as expected and large water balance errors could occur if resistance values were smaller than 1 x 10^9 s. These errors were traced to an incomplete root uptake algorithm which was modified. The strong effect of SRCR on transpiration suggested that the model should dynamically change SRCR as a function of, perhaps, temperature, growth stage, xylem water potential, etc. Future work will focus on including a dynamic SRCR in the root water uptake algorithm as well as including changes in the soil hydraulic resistance as a function of soil drying. Discretization analysis showed that thickness of the top soil layer should not surpass 0.002 m if accurate partitioning of ET into evaporation and transpiration is required. Partitioning of ET into E and T was also affected by the values used for the surface roughness length and the plant hydraulic resistance. ENWATBAL.BAS is a useful tool for investigating the complex mechanisms of evapotranspiration.

APPENDIX

The three implicit sets of equations defining, respectively, the leaf water potential, leaf temperature and soil surface temperature in energy balance terms, are each solved by implicit equation solvers written as three separate BASIC functions, IMPL1, IMPL2 and IMPL3. The equations solved in each function are given below.

Function IMPL1

The implicit set of equations describing the canopy water potential, WPOTCR (m), begins with:

$$CL1 = f(WPOTCR) \qquad [A1]$$

where CL1 is that part of epidermal conductance (m s^{-1}) that is a function of canopy water potential. In the program the value of CL1 is given by the program function AFGEN, which uses a tabular description of the dependence of CL1 on WPOTCR provided by the user. The overall epidermal conductance per unit leaf area index, CL (m s^{-1}) is:

$$CL = 2/(CL1^{-1} + CL2^{-1}) \qquad [A2]$$

where CL2 is that part of epidermal conductance (m s^{-1}) that is a function of solar radiation (calculated beforehand). The overall epidermal resistance, RL (s m^{-1}) is adjusted for leaf area index (LAI):

$$RL = CL^{-1}\, LAI^{-1} \qquad [A3]$$

The resistance to latent heat flux, CRV (s m^{-1}), is the sum of the turbulent resistance, CRH (s m^{-1}) (calculated daily as a function of LAI), and of the canopy (big leaf) epidermal resistance, RL:

$$CRV = CRH + RL \qquad [A4]$$

Transpiration rate, LTR (J m^{-2} s^{-1}), depends on the gradient of absolute humidity between leaf, HL (kg m^{-3}), and air, HA (kg m^{-3}); the latent heat of vaporization, LH (J kg^{-1}), and the resistance. Note that aerodynamic resistances for sensible and latent heat flux are assumed equal.

$$LTR = (HL - HA)\ LH/CRV \qquad [A5]$$

Finally, the potential gradient between soil and leaf divided by the crop hydraulic resistance, SRCR (s) (adjusted for leaf area index, LAI), and multiplied by the latent heat of vaporization, LH, must equal the transpiration rate, LTR:

$$0 = (WPSEFF + WPCRMX - WPOTCR)\ (1000\ LH) \cdot (LAI/SRCR) - LTR \qquad [A6]$$

where WPSEFF is the effective soil water potential (m), WPCRMX is the maximum canopy water potential (m). The implicit equation root finding subprogram attempts to minimize the value of Equation A6.

Function IMPL2

The implicit set of equations describing the canopy (big leaf) temperature is:

$$LWRC = \sigma\ (TL + 273.16)^4 \qquad [A7]$$

where LWRC is the canopy longwave emission (J s^{-1} m^{-2}) described by the Stefan-Boltzmann law and σ is 5.67 x 10^{-8} J s^{-1} m^{-2} K^{-4}. Emissivity is taken equal to 1. The net radiant energy input to the canopy, NRBC (J s^{-1} m^{-2}), is:

$$NRBC = GR \times ABSC + (1 - FTSR)\ (SKL - LWRC) \qquad [A8]$$

where GR is the shortwave solar radiation (J s^{-1} m^{-2}), ABSC is the absorptance of the canopy (calculated at the start of each day as a function of leaf area index), FTSR is transmittance of the canopy (also calculated each day as a function of LAI), and SKL is the long wave radiation from the sky (J s^{-1} m^{-2}). The leaf absolute humidity, HL (kg m^{-3}) (within the stomates, not corrected for leaf water potential), is:

$$HL = \frac{1.323 \exp[17.27\,TL/(237.3 + TL)]}{(273.16 + TL)} \qquad [A9]$$

The transpiration rate, LTR (J s^{-1} m^{-2}), is:

$$LTR = (HL - HA)\ LH/CRV \qquad [A10]$$

where LH is the latent heat of vaporization (J kg^{-1}) calculated as a function of leaf temperature, HA is the absolute humidity of the air (kg m^{-3}), and CRV is the resistance to latent heat flux (s m^{-1}). The canopy-air sensible heat exchange, SHCA (J s^{-1} m^{-2}), is:

$$SHCA = LTR - NRBC \qquad [A11]$$

Finally, the canopy-air temperature difference divided by the turbulent resistance, CRH, and multiplied by the heat capacity of the air, SH (J m^{-3} C^{-1}), must equal the sensible heat flux.

$$0 = (TA - TL)\ SH/CRH - SHCA \qquad [A12]$$

Equation A12 is minimized by the implicit root finding function.

Function IMPL3

The implicit set of equations describing the soil surface temperature, TS (C), begins with:

$$LWRS = \sigma\ (TS + 273.16)^4 \qquad [A13]$$

where LWRS is the long wave emission by soil (J s^{-1} m^{-2}). The net radiation balance at soil surface, NRBS (J s^{-1} m^{-2}), is:

$$NRBS = GR \times ABSSa + (1 - FTSR)\ LWRC + FTSR \times SKL - LWRS \qquad [A14]$$

where ABSSa is the soil absorptance and the other terms are defined above. The potential humidity, HO (kg m^{-3}), at the soil surface temperature is:

$$HO = \frac{1.323 \exp[17.27\,TS/(237.3 + TS)]}{(273.16 + TS)} \qquad [A15]$$

And the actual humidity of the first soil layer, HS (kg m^{-3}), is:

$$HS = HO \times \exp\left[\frac{PPOT_1}{46.97(TS + 273.16)}\right] \qquad [A16]$$

where $PPOT_1$ is the soil water potential (m) of the first layer. The latent heat flux, LEVS (J s^{-1} m^{-2}), between the soil and atmosphere is:

$$LEVS = (HS - HA)\ LH/RS \qquad [A17]$$

where RS is the aerodynamic resistance (s m^{-1}) and the other terms are defined above. The sensible heat flux between soil and air, A (J s^{-1} m^{-2}), is:

$$A = (TS - TA)\ SH/RS \qquad [A18]$$

The soil heat flux, S (J s^{-1} m^{-2}), is calculated as the residual of net radiation, sensible heat flux and latent heat flux:

$$S = NRBS - A - LEVS \qquad [A19]$$

Finally, the temperature gradient between soil surface and middle of the top soil layer, multiplied by the thermal conductivity, must equal the soil heat flux:

$$0 = (TS - TEMP_1)\ (KOND_1/DIST_1) - S \qquad [A20]$$

Equation A20; where $TEMP_1$ is the temperature of the top soil layer (C), $DIST_1$ is the distance from the surface to the center of the top soil layer (m) and $KOND_1$ is the thermal conductivity of the top soil layer (J s^{-1} m^{-1} C^{-1}); is minimized by the implicit root finder.

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