SURFTEMP: Simulation of Soil Surface Temperature Using the Energy Balance Equation

S.D. Wullschleger,* J.E. Cahoon, J.A. Ferguson, and D.M. Oosterhuis

ABSTRACT

Energy exchange at the soil surface and the temperature conditions that result are fundamental to our understanding of how soil properties interact with the physical environment. However, these concepts are often difficult to effectively convey in the classroom because of the complexity by which radiant energy is dissipated in the microclimate. Therefore, a computer simulation model was developed as an educational tool to assist instructors in illustrating how differences in geographic, climatic, and edaphic considerations can influence energy conversion at the soil surface. The model, SURFTEMP, uses a number of radiant and thermal transport formulae that, when substituted into the energy balance equation, can be solved simultaneously for soil surface temperature. For each diurnal simulation, printouts provide detailed information on the radiant, sensible, conductive, and latent exchange processes and the soil temperatures that subsequently develop. Specifically, the program provides a summary of user-selected inputs and a series of tables for hourly estimates of solar radiation components, energy balance components, actual and potential evaporation, soil temperatures by soil depth, and volumetric water content by soil depth. This article briefly describes the development of this model and illustrates its utility in demonstrating certain educational principles related to the energy balance equation.

RADIANT ENERGY received at the earth's surface and the soil temperatures that result are central to the interests of many in the agricultural sciences. For example, soil temperature is of importance in determining biological processes such as seed germination, seedling growth, root development, and microbial activity. However, because of the complexity by which radiant energy is dissipated within the microclimate, differences in geographic, climatic, and edaphic properties can decidedly influence soil temperature. Understanding the principles which govern energy exchange at the soil surface can help demonstrate the fundamental relationships that exist among agronomic disciplines.

Soil temperature varies in response to the exchange of radiant, sensible, and latent energy at the soil surface (Hillel, 1982). Effects of these phenomena are propagated by a series of transport processes, many of which can be described mathematically and incorporated into computer simulation models (Jones, 1983; Gupta et al., 1984). Several models have been developed for the prediction of soil temperature, many of which have adopted either an empirical (Fluker, 1958; Parton and Logan, 1981) or a mechanistic approach (Myrup, 1969; Goudriaan and Waggoner, 1972; Bristow, 1987). Although both approaches can be used for predictive purposes, the mechanistic model has greater scope for application and can lead to important advances in understanding system behavior under an array of conditions (Jones, 1983).

The objective of our current efforts has been to develop a model based on the energy balance equation for simulation of the soil temperature. Our primary concern was that the model be developed as an educational tool, and therein encourage students to understand how geographic, environmental, and edaphic variables can impact energy exchange and temperatures at the soil surface. Specific objectives of this article are to describe the model's development, to discuss the user-selectable output options, and to illustrate some educational applications of the model.

MODEL DESCRIPTION

The governing equation used in the SURFTEMP model was derived as a functional form of the energy balance, in units of watts/meter^2

$$RN + S + G + LE + P + M = 0 \quad [1]$$

where RN is net solar radiation, S is sensible heat flux, G is soil heat flux, LE is latent heat flux, P is energy used in photosynthesis, and M is any metabolic energy expenditures (Rosenberg et al., 1983). Since the system being modeled was for a bare soil surface containing no plants, the terms P and M were neglected. Thus, radiant energy received at the earth's surface must be dissipated solely through the transport processes of S, G, and LE (Fig. 1). The sign convention used in this model assumed that heat transfer to the soil surface was positive, while heat transfer away was negative.

Net Solar Radiation

Net radiation was determined by estimating the relative contribution of both the incoming shortwave (RS) and longwave solar radiation

$$RN = RS(1 - r) + RLN \quad [2]$$

where r is reflectance or albedo of the soil surface and RLN is net longwave solar radiation. Incoming shortwave solar radiation was determined as outlined in American Society of Heating, Refrigeration, and Air Conditioning

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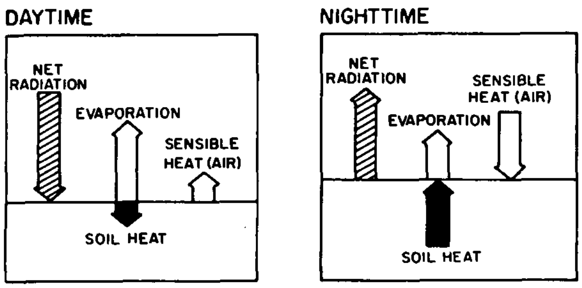

Fig. 1. Schematic representation of the daytime and nighttime energy balance where radiant energy is dissipated by soil heat, sensible heat, and latent heat flux (Adapted from Tanner, 1968).

Engineering (1981). This method calculates both direct and diffuse solar radiation at the surface as a function of the solar constant, location, day of year, hour of the day, and cloud cover using a generated extinction coefficient. Incoming longwave radiation was calculated based on hourly air temperature and cloud cover (Rosenberg et al., 1983). Outgoing longwave radiation was estimated as a function of soil surface temperature to the fourth power and assumed a soil emissivity of one.

Sensible Heat Flux

The sensible heat flux was determined according to Rosenberg et al. (1983)

$$S = P_a C_p (T_a - T_s)/R_a \qquad [3]$$

where P_a is the density of air, C_p is the specific heat of air, T_a and T_s are the air and soil temperature, respectively, and R_a is resistance to sensible heat transfer. Resistance to sensible heat transfer in forced convection was described as

$$R_a = 307(D/U)^{1/2} \qquad [4]$$

where D is the characteristic dimension and U is the wind speed.

Soil Heat Flux

Since steady-state temperatures rarely exist, soil heat flux could not be solved directly by Fourier's law (Wolf, 1983). Therefore, we equated the differential heat flux and heat storage as a function of small soil depth increments (1 cm) in order to give the transient heat flow equation

$$\partial G/\partial z = C(\partial T/\partial t) \qquad [5]$$

where $G = K(\partial T/\partial t)$, K is the soil thermal conductivity, C represents the volumetric heat capacity, T is temperature, z is depth, and t is time. For homogeneous soils, Eq. [5] can be simplified (Incropera and De Witt, 1985) and rewritten as

$$\partial T/\partial t = \alpha(\partial^2 T/\partial z^2) \qquad [6]$$

Table 1. Variable description and default values of variables that can be altered by the user of program SURFTEMP.

Variable description	Default value
Geographic considerations	
Day of year	180
Location latitude	35°
Location longitude	95°
Climatic variables	
Minimum air temperature	25°C
Maximum air temperature	35°C
Soil temperature at 30 cm	25°C
Precipitation	0 mm
Cloud cover	20%
Wind	2 m/s
Soil physical properties	
Soil bulk density	1325 kg/m^3
Porosity	50%
Soil reflectivity	25%
Soil conductivity curve	
Intercept	0.23 W/(m K)
Slope	7.0 W/(m K)
Irrigation	0 mm

where T is temperature, t is time, z is soil depth, and α is the thermal diffusivity. The finite difference of Eq. [6] is

$$T_i^{l+1} = T_i^l + \Gamma\,(T_{i+1}^l - 2T_i^l + T_{i-1}^l) \qquad [7]$$

where l is an indicator of the time increment, i is the depth increment, and Γ is the expression $[(\alpha\Delta t)/(\Delta z)^2]$. For a soil of known thermal properties, Eq. [7] will yield the diurnal soil temperature profile.

Volumetric heat capacity was calculated as a function of soil porosity and water content, with a default heat capacity for the soil parent material of 825 J/(kg K). Soil thermal conductivity was assumed to vary linearly with soil moisture content as outlined by Al-Nakshabandi and Kohnke (1965). The slope and intercept coefficients for the soil thermal conductivity vs. soil moisture equation are defaulted to 7 and 0.23 W/(m k), respectively. These parameters can be changed at the time of model execution.

Latent Heat Flux

Latent heat flux represents that portion of the radiant energy used to evaporate water. Potential evaporation of water from the soil profile was calculated using a modified Makkink equation (Makkink, 1957)

$$EP = RN\,[\beta/(\beta + \gamma)] \qquad [8]$$

where EP is the potential evaporation (W/m^2), β is the slope of the saturated vapor pressure-temperature curve, and γ is the psychrometric constant. Using Eq. [8], hourly estimates of the latent energy (LE) expenditure were calculated as the product of EP and a factor that indicated the relative availability of water at the soil surface (Ritchie, 1972). The appropriate soil water properties, including maximum soil water content, maximum Stage 1 and Stage 2 evaporation parameters, cumulative evaporation since the last precipitation or irrigation, surface water content, and soil water content at the 30-cm depth, can be altered or accepted as specified in the model.

Volumetric soil water content was initially assumed to vary linearly with depth from specified water contents at the soil surface and at the 30-cm depth. When water was added (precipitation or irrigation), the change in volumetric water content was changed in successive depth increments to the maximum water content until the applied water was totally distributed throughout the soil profile. Evaporation was apportioned to the successive soil depths, in accordance with the ratio of actual to maximum water content, until the computed evaporative demand was satisfied. We recognize that ignoring unsaturated water flow with respect to water distribution in the soil is an inaccuracy; however, for short periods (24 h), this was acceptable in order to simplify model execution.

Solution to Energy Balance

The equations described above provided the necessary relationships depicting each of the terms in Eq. [1]. Net solar radiation and latent heat flux were determined independent of the soil surface temperature, while outgoing longwave radiation, soil heat flux, and sensible heat flux were expressed as functions of soil surface temperature. The energy balance equation was solved for soil surface temperature, and temperature distributions with depth in the soil determined for a given 24-h-simulation period.

INPUT OPTIONS

All user inputs are prompted by on-screen questions which are grouped into either geographic, environmental, or edaphic considerations. Within each of these categories, the user has the option to select and modify any of the variables shown in Table 1. Program SURFTEMP has a series of default values which can easily be changed to reflect a range of soil properties and climatic conditions for locations anywhere in the USA.

Classroom demonstration of how these parameters influence the components of the energy balance equation and soil temperature can best be achieved by altering each parameter individually. In this manner, students can visualize how subtle differences in day of year, latitude, precipitation, cloud cover, soil reflectivity, bulk density, and other variables can alter the radiant, thermal, and latent exchange processes at the soil surface. However, students should be made aware that certain variables do not necessarily change independently of others, such as surface wetness and soil reflectivity, or bulk density and soil porosity (Hillel, 1982).

PROGRAM OUTPUT

For each diurnal simulation, the user may generate summaries for any of the following output categories:

1. Solar radiation components,
2. Energy balance components,

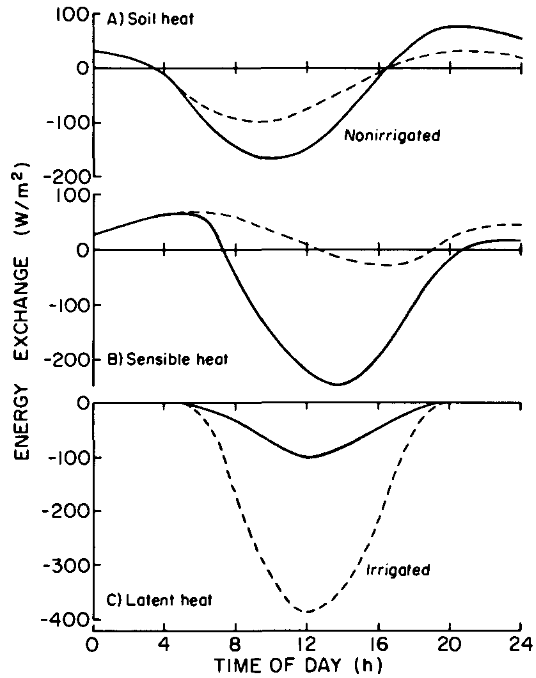

Fig. 2. Illustration of the diurnal energy exchange processes due to (A) soil heat, (B) sensible heat, and (C) latent heat fluxes for an irrigated (10 mm) and a nonirrigated soil.

3. Evaporation components,
4. Soil temperatures by time of day,
5. Soil temperatures by soil depth, and
6. Volumetric water content by soil depth.

Each simulation output consists of a list of initial variable values (Table 1) and extensive information concerning the specific output option selected. From these outputs, students can either tabulate or graphically illustrate a number of useful concepts related to the energy balance equation. Application of the program SURFTEMP without an instructor may give acceptable results; however, the usefulness of the program with respect to classroom discussion will depend upon the instructor's ability to separate and demonstrate important and subordinate aspects of specific problems.

For demonstration purposes, probably the most dramatic application of this program is to observe how irrigation or precipitation can affect energy exchange processes at the earth's surface and, hence, soil temperatures. Graphic illustration of the energy balance equation for a dry and wet soil surface (following a 10-mm irrigation) showed how the input of water can significantly alter radiant and thermal energy conversion (Fig. 2). Both irrigated and nonirrigated soils had similar patterns of energy exchange prior to sunrise due to the lack of radiation to drive energy conversion. However, with the receipt of radiant energy at the soil surface, differences between the dry and wet soils became apparent. The dry soil dissipated over 30% of the incident radiant energy via soil heat flux (Fig. 2A) and almost 45% via sensible heat flux (Fig. 2B). In contrast, the wet soil dissipated energy primarily through latent heat

Table 2. Midday components of the energy balance equation as simulated by program SURFTEMP for an irrigated (10 mm) and a nonirrigated soil.

Parameter	No irrigation	Irrigation
	(W/m^2)	
Net radiation	412	604
Soil heat flux	−128	−60
Sensible heat flux	−184	−17
Latent heat flux	−100	−527

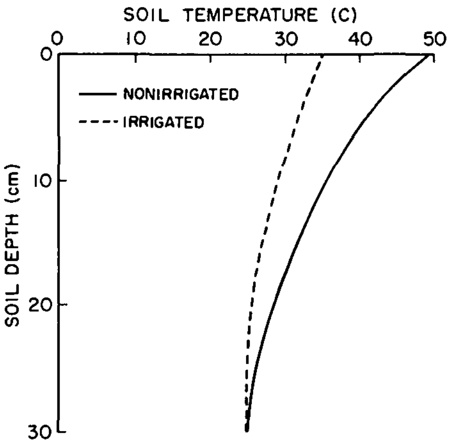

Fig. 3. Simulation of soil temperature by depth for an irrigated (10 mm) and a nonirrigated soil.

exchange (evaporation of soil water) which exceeded 85% of the diurnal net radiant energy (Fig 2C). Tabulation of the energy balance components at midday for the irrigated and nonirrigated soils also shows that differences in energy exchange can be quite substantial (Table 2). Net radiation is considerably lower for the dry soil due to a higher reflectance or albedo (0.35 vs. 0.20 for the dry and wet soils, respectively). All other variables are those default values shown in Table 1.

The impact of how energy is exchanged at the soil surface can also be observed by plotting soil temperatures by depth for both the irrigated and nonirrigated soils (Fig. 3). In this example, dry soil temperatures at the soil surface increased dramatically over ambient air temperature (35 °C) due to soil heat flux, while evaporative cooling at the wet soil surface maintained soil temperatures at or below ambient. Because of the dampening effect of soil depth on temperature, the thermal profiles of both soils were similar at depths greater than 30 cm. This example readily illustrates the importance of latent heat exchange in energy dissipation and how irrigation can effectively reduce midday soil surface temperatures by over 15 °C.

Program SURFTEMP incorporates on-screen graphic routines to illustrate the energy balance equation and its components, but these routines are specific for EGA or VGA monitors, 80 × 43 text, and 640 × 340 graphics mode. The user has the option to download information concerning the energy balance equation to an ASCII file for use in other popular graphic packages such as LOTUS 1-2-3 or QUATTRO. Where these programs are not available, illustration of data from the printouts is a simple assignment, particularly when student groups are asked to address different but complementary problems.

CONCLUSION

The modeling approach utilized in program SURFTEMP calculates the diurnal radiant energy received at the soil surface and, subsequently, partitions that energy to the fundamental components of the energy balance equation. Because the model simulates the conversion of energy for an array of input parameters, SURFTEMP provides an excellent educational opportunity to illustrate the importance of geographic, climatic, and edaphic influences on the soil microclimate. Such illustrations serve to highlight the relationships among several agronomic disciplines including soil physics and micrometeorology.

SOFTWARE SPECIFICATION

Program SURFTEMP consists of a compiled file, BALANCE.EXE, totaling 78 kB for use with DOS 2.0 or higher, on an XT, AT, or other IBM-PC compatible computer. The program was written and compiled in Microsoft Quick-BASIC and requires 256 k RAM. The use of a printer is necessary for data output. Program SURFTEMP is public domain software and will be supplied free, along with documentation, upon receipt of a blank 5¼ in. diskette and postpaid mailer. Users are encouraged to make this software available to interested persons and may alter the source code as desired. Send requests to Dr. J.A. Ferguson, Dep. of Biological and Agricultural Engineering, Univ. of Arkansas, Fayetteville, AR 72701.

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