United States
Department of
Agriculture

Forest Service

Southeastern Forest
Experiment Station

Research Paper
SE-281

A Soil Temperature Model for Closed Canopied Forest Stands

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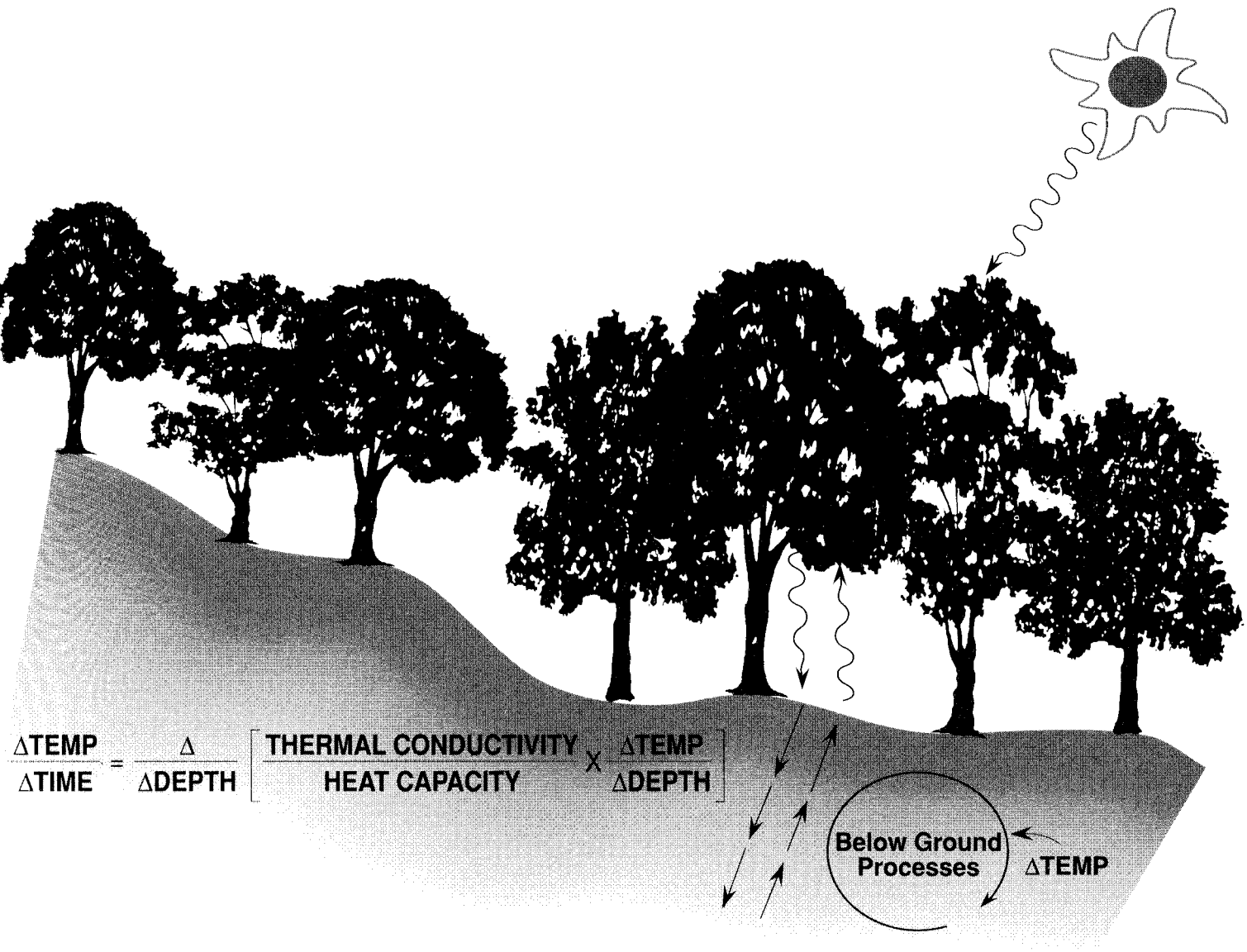

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April 1991

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ABSTRACT

We developed a soil temperature model to predict hourly temperatures at the litter-soil interface and at soil depths of 0.10 m, 0.20 m, and 1.25 m in hardwood forest stands with closed canopies. The model, which was written in BASIC on a microcomputer, uses a numerical solution for the partial differential heat-flow equation. Litter-soil interface temperature was predicted from air temperature by multiple regression. Daily temperatures at the litter-soil interface and in the soil were predicted for 2-month periods in summer, late fall, and early spring. Predictions were most accurate in summer and late fall but tended to be high in late spring. Results were in general agreement with measured values when approximate soil thermal characteristics were used. Predicted values were within 1 to 3 $^{\circ}C$ of measured soil temperatures. Soil temperature prediction could be improved by using actual thermal characteristics; however, sensitivity analyses indicate that only large variations in thermal characteristics significantly affect soil temperature predictions. The model predicts soil temperatures within the bounds (± 5 $^{\circ}C$) of most microbial activity assays and should be suitable for regulating rate functions in nutrient and carbon cycling models.

Keywords: Computer model, soil heat flow, litter-soil interface temperature, hourly soil temperature, seasonal variation, BASIC.

In forest ecosystems, soil temperature regulates many processes, such as microbial transformations of nitrogen (Plymale and others 1987) and sulfur (Fitzgerald and others 1983; Strickland and Fitzgerald 1984), organic matter decomposition (Waide and others 1988), and root growth, activity, and respiration (Marshall and Waring 1985). Temperatures throughout the soil profile, however, are difficult to measure over large areas for long periods. Thus, a soil temperature prediction model that uses readily obtainable inputs would have great utility for estimating or interpreting rates of ecosystem processes. Several models are available for clearcut forests and agricultural fields (Hanks and others 1971; Stathers and others 1985; Wierenga and de Wit 1970), but no soil temperature models have been developed for undisturbed forests. The objective of our study was to develop a soil temperature model adaptable to a variety of site conditions in undisturbed forests.

Methods

Changes in soil temperature over time were simulated by using the partial differential equation:

$$dT/dt = d/dz[(ka/Cs)(dT/dz)] \qquad (1)$$

where T is soil temperature, t is time, z is depth, ka is apparent thermal conductivity in Watts meter^{-1} minute^{-1} Kelvin^{-1} (W m^{-1} min^{-1} K^{-1}), and Cs is volumetric heat capacity in Megajoules meter^{-3} Kelvin^{-1} (MJ m^{-3} K^{-1}). Thermal conductivity is a measure of the rate of heat transfer per unit of temperature gradient. Volumetric heat capacity is a measure of the heat storage of soil. It can be measured directly, estimated by summing the heat capacities of individual constituents (e.g., sand, clay, silt), or computed as a function of bulk density and soil water content (De Vries 1963). Thermal diffusivity (α) is the ratio of ka/Cs (m^{-2} min^{-1}) and is used in the numerical solution of equation (1). The model predicts soil temperature at four depths: the litter-soil interface and 0.10 m, 0.20 m, and 1.25 m below the soil surface. Rather than measure the thermal properties of our soils, we used approximate values obtained from the literature. For heat flow between the litter-soil interface and the 0.10-m soil depth, an α of 0.001 was used (Van Wijk and De Vries 1963). For the 0.10-m to 0.20-m-depth increment, we used an α value of 0.0015; for the 0.02-m to 1.25-m-depth increment, we used an α value of 0.0018 (Hanks and others 1971). No adjustments were made for changes in α with soil temperature or moisture.

Equation (1) was solved numerically using the Crank-Nicolson finite difference approximation and the Thomas algorithm (Ames 1979). Solution procedures were written in BASIC on a microcomputer. The time step for the numerical solution is a user-defined variable. Soil temperature data presented in this paper were simulated with an hourly time step. Numerical solution required

providing upper and lower boundary temperatures and initial temperatures for each soil depth. The litter-soil interface temperature was used as the upper boundary. Multiple regression was used to predict litter-soil interface temperatures. The equation was of the form:

$$\text{litter-soil temperature} = a + b_1 * X_1 + b_2 * X_2 \quad (2)$$
(mean hourly in ^oC)

where X_1 = mean hourly air temperature beneath the forest canopy and X_2 = mean (24 hr) air temperature beneath the forest canopy of the previous day. The X_2 variable was included to account for the residual effects of heating or cooling of the litter-soil interface from temperatures of the previous day. Litter-soil temperature changes due to latent heat loss and/or radiation were not considered. The lower boundary (> 1.25 m) was defined as the average monthly temperature at 1.25 m. These data were obtained from hourly measurements taken in 1983 within a mixed hardwood stand described below. The lower boundary temperature was held constant within each month; however, the lower boundary temperature was allowed to vary across months.

Data used in regression development and model validation were from a climatic station (Coweeta Hydrologic Lab CS-17) located in a forested northeast-facing watershed in the Southern Appalachians of North Carolina. Elevation of CS-17 is approximately 880 m. Overstory conditions at the monitoring site included a deciduous forest canopy and an evergreen shrub understory (primarily *Kalmia latifolia* L.). Leaf area index (m^2 m^{-2}) of the overstory is approximately 5.0. Temperature at the litter-soil interface and soil temperature at 0.10 m were monitored continuously during 1983 using thermocouples and a strip chart recorder. Air temperature was measured with a thermister located approximately 1 m above the forest floor. For soil temperatures at depths of 0.20 m and 1.25 m, we used data collected during 1983 from a soil pit approximately 450 m from CS-17. Equation (2) was parameterized using mean hourly air and litter-soil temperature data obtained on 1 or 2 randomly selected days during each month of 1983. The ability to generalize equation (2) was evaluated in two ways. First, equation (2) was parameterized using comparable data from a south-facing climatic station (CS-21). Climatic station 21 is approximately 1 km from CS-17, is located at an elevation of approximately 840 m, and has overstory and understory characteristics similar to CS-17. Our purpose here was to determine if a regression approach, using air temperature as an independent variable, would be appropriate (i.e., be statistically significant and have a high R^2 value) on south-facing watersheds as well. Second, the CS-17 and CS-21 regression models were applied to data from CS-17, and the resulting litter-soil predictions were compared. In this assessment, similar predictions would indicate that relationships established at one location in the watershed would be at least generally applicable in other locations.

Simulation required input of mean hourly air temperature and the mean (24-hr) air temperature of the previous day, initial temperatures for each soil depth, and the lower boundary temperature for each month. Model output included hourly temperatures at the litter-soil interface and at soil depths of 0.10 m, 0.20 m, and 1.25 m, as well as 24-hour means. Variations in soil temperature were simulated for 2-month periods. Simulations are presented for June and July, November and December, and February and March. Although the model predicts soil temperature on an hourly basis, diurnal variations in measured temperatures were slight. Thus, simulation results are presented as 24-hour means.

Sensitivity analyses were used to determine the significance of: (1) the use of approximate soil thermal properties and (2) the use of fixed α values with respect to moisture and temperature. These analyses were performed by varying the α parameters and comparing simulation results with measured soil temperature values. In addition, the lower boundary temperature was varied by $\pm 3\ ^oC$ to evaluate the influence of a fixed monthly lower boundary temperature on soil temperature at depths of 0.10, 0.20, and 1.25 m.

Results and Discussion

Litter-Soil Interface Prediction Equations

The regression relating mean hourly temperature at the litter-soil interface (Y) to mean hourly air temperature (X_1) and mean (24 hr) air temperature of the previous day (X_2) on CS-17 was highly significant (r^2=0.95, P<0.001, n=481). An equally strong regression (r^2=0.96, P<0.001, n=480) was observed when data from CS-21 were used. Furthermore, using the independent data set from CS-17, we found litter-soil temperature predictions to be in agreement when both the CS-17 and the CS-21 regression models were used. This agreement in temperature predictions (fig. 1) indicates that, on a local scale, litter-soil vs. air temperature prediction equations may be broadly applicable.

In contrast to our approach, Stathers and others (1985) used detailed surface energy-balance equations to predict heat flux at the soil surface (i.e., upper boundary) in their soil temperature model for a clearcut forest. Over a 24-hour simulation period their model predicted surface temperature within 3 ^{o}C of measured values during the day and within 1 ^{o}C at night. However, the energy balance in forested systems is more complex than in clearcuts because the forest canopy influences energy input to the soil surface (Swift 1972). Similarly, undisturbed forests have a litter layer that, because of processes such as insulation and latent heat loss from evaporation, adds complexity to surface energy-balance equations. These factors prompted an empirical approach to predicting litter-soil temperature. Also, while perhaps sacrificing precision, a simple empirical model reduced meteorological data requirements. Gupta and others (1981) used a similar approach to estimate surface temperature in agricultural fields.

Predictions

Predicted and measured temperatures for June and July agreed reasonably well at all soil depths (fig. 2). Predicted values were usually within 1 to 2 ^{o}C of the measured values; however, the model consistently overpredicted litter-soil temperature (by as much as 2.5 ^{o}C) in early June (table 1). Predictions at the 0.10-m soil depth were in general agreement with measured values; errors ranged from 1.5 ^{o}C above to 2.5 ^{o}C below measured values.

Most predictions (68 percent) were within 1 oC of measured values (table 1). Consistent with heat-flow theory (Carslaw and Jaeger 1959), predicted soil temperatures at 0.10 m closely paralleled measured litter-soil temperature fluctuations. However, measured data showed a constant soil temperature during a 19-day time period. Because of the large fluctuations in litter-soil temperature, we hypothesize that the patterns shown in the measured data at 0.10 m are due to temperature probe and/or chart recorder insensitivity. Although the model adequately predicted soil temperature at 0.20 m in early June, temperatures were consistently underestimated thereafter. Seventy-two percent of the predicted soil temperatures at 0.20 m were 1 to 2 ^{o}C lower than measured values (table 1). Similar patterns were observed for the 1.25-m soil depth.

Results of predicted-measured comparisons in November and December were similar to the results in June and July (fig. 3). Litter-soil temperatures were predicted reasonably well by the regression model (e.g., 70 percent of predicted values were within 1 ^{o}C of measured values; table 1), but temperatures at the 0.10-m soil depth were consistently underestimated by 1 to 2 ^{o}C. At the 0.20-m soil depth, the model consistently overestimated soil temperature by 1 to 2 ^{o}C; however, the patterns of temperature variation predicted by the model were consistent with measured values. Good agreement was found between measured and predicted temperatures at the 1.25-m soil depth.

In February and March, the litter-soil temperatures were overestimated by the model (fig. 4). Fifty percent of the predicted values deviated more than 2 ^{o}C from measured values (table 1). Predicted and measured mean daily temperatures at the litter-soil interface were 5.3 and 3.6 ^{o}, respectively. At 0.10-m soil depth, the simulated soil temperatures followed a pattern similar to measured values. Model values, however, were more variable. In addition, predicted soil temperatures at 10 cm were not in phase with measured values (i.e., predicted temperatures increased sooner than measured temperatures). Soil temperature at 0.20 m was closely simulated by the model. Although simulated values at 0.20 m were generally greater than measured values (e.g., 69 percent of predicted values were 1 to 2 ^{o}C greater than measured values; table 1), patterns of temperature variation over the simulation period were

essentially identical. At the 1.25-m soil depth, the model consistently underestimated soil temperature (table 1). At this depth, temperature variations were also underestimated.

There are several possible explanations for the differences between predicted and actual soil temperature values. First, we used constant and approximate soil thermal characteristics for each soil-depth increment. Flint and Childs (1987) demonstrated the importance of determining actual soil thermal characteristics, and these characteristics change with varying soil moisture and temperature. Where more accuracy is required, actual thermal properties should be used in the model. Second, our validation data were spatially separate. We assumed that the thermal characteristics of the upper layers at CS-17 were identical to those of the soil pit. Some of the model inaccuracies may be related to differences in thermal properties between the two measurement sites. Finally, because surface temperature is probably the most critical component in soil heat flux (Stathers and others 1985), an improved model for litter-soil prediction may increase overall model accuracy. Despite these sources of variability, however, the model predicted mean daily temperatures fairly accurately. In most cases, predictions were within 1 to 3 $°C$ of actual values and the patterns of daily average temperature fluctuations were predicted accurately. Studies of temperature regulation of microbial processes, for example, frequently use 5 $°C$ temperature increments in incubation assays. Thus, the predictive capability of the soil temperature model is within the sensitivity bounds of biological response data, and the model should be adequate to regulate rate functions in most ecosystem process models.

Sensitivity Analyses

Soil temperatures in March were used to perform sensitivity analyses. We chose March because soil moisture is usually high in this month and thus the approximate α values would potentially be most inaccurate. Hence, we expected the greatest difference in simulated soil temperatures when α values were varied in this month. Using various combinations of α parameters, we compared simulation results with the measured data. For comparison with predictions, we used approximate α values. Results reported here are for the most dramatic parameter manipulations. For example, figure 5A presents simulation results when we used an α value of 0.0001 m^2 min^{-1} for all depth increments. The primary result was a reduction in the magnitude of temperature variations. A secondary result was an alteration of the timing of changes in soil temperature. Predictions were improved at the 0.10-m depth but were less accurate at the 0.20-m and 1.25-m soil depths. In contrast, increasing the α values to 0.0036 m^2 min^{-1} for all depth increments (fig. 5B) increased the magnitude of temperature variation. Predictions were less accurate for the 0.10-m and 0.20-m soil depths but were improved for the 1.25-m soil depth. These large changes in α parameter values resulted in, at most, an increased overprediction of about 2 $°C$. Simulations with less dramatic parameter changes yielded smaller errors. Consistent with Stathers and others (1985) and Hanks and others (1971), these results indicate that approximate α values will provide reasonable soil temperature predictions.

Changing the lower boundary temperature by $\pm 3°C$ had little influence (<0.5 $°C$ difference) on soil temperature at 0.10 m. At 0.20 m, soil temperatures differed from the model using the actual lower boundary temperature by about 1 $°C$. As expected, changes were greatest at the 1.25-m soil depth. Predicted soil temperature at 1.25 m was 2 $°C$ higher when the lower boundary temperature was increased by 3 $°C$, and 2 $°C$ lower when the lower boundary was decreased by 3 $°C$.

Conclusions

Simulation results indicate that reasonable estimates of soil temperature in forested stands can be obtained with easily measured climatic data and approximate soil thermal characteristics. These properties are highly desirable in models used for predicting soil temperature at remote locations. More accurate estimates may be possible with the input of site-specific estimates of soil thermal characteristics.

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Table 1—Deviation of predicted soil temperature from measured soil temperature, by month and depth. Data are number (percent) of days when predicted values are within a given temperature deviation range.

	Deviation (°C)						
Soil depth	<-2	-2	-1	±0.5	1	2	>2
				JUNE and JULY			
Litter-soil interface				36(60)	11(18)	12(20)	2(3)
0.10 m	4(7)	10(16)	8(13)	32(52)	2(3)	5(8)	
0.20 m		32(52)	12(20)	14(23)	3(5)		
1.25 m		35(57)	14(23)	11(18)	1(2)		
				NOVEMBER and DECEMBER			
Litter-soil interface	4(8)	5(9)	8(15)	20(38)	9(17)	7(13)	
0.10 m	2(4)	18(34)	11(21)	18(34)	4(8)		
0.20 m				3(5)	9(17)	36(68)	5(9)
1.25 m			3(5)	48(91)	2(4)		
				FEBRUARY and MARCH			
Litter-soil interface	1(2)	4(7)	6(10)	6(10)	4(7)	8(14)	29(50)
0.10 m	5(9)	16(28)	9(16)	4(7)	5(9)	11(21)	8(14)
0.20 m			3(5)	15(26)	14(24)	26(45)	
1.25 m	2(3)	12(21)	33(57)	11(21)			

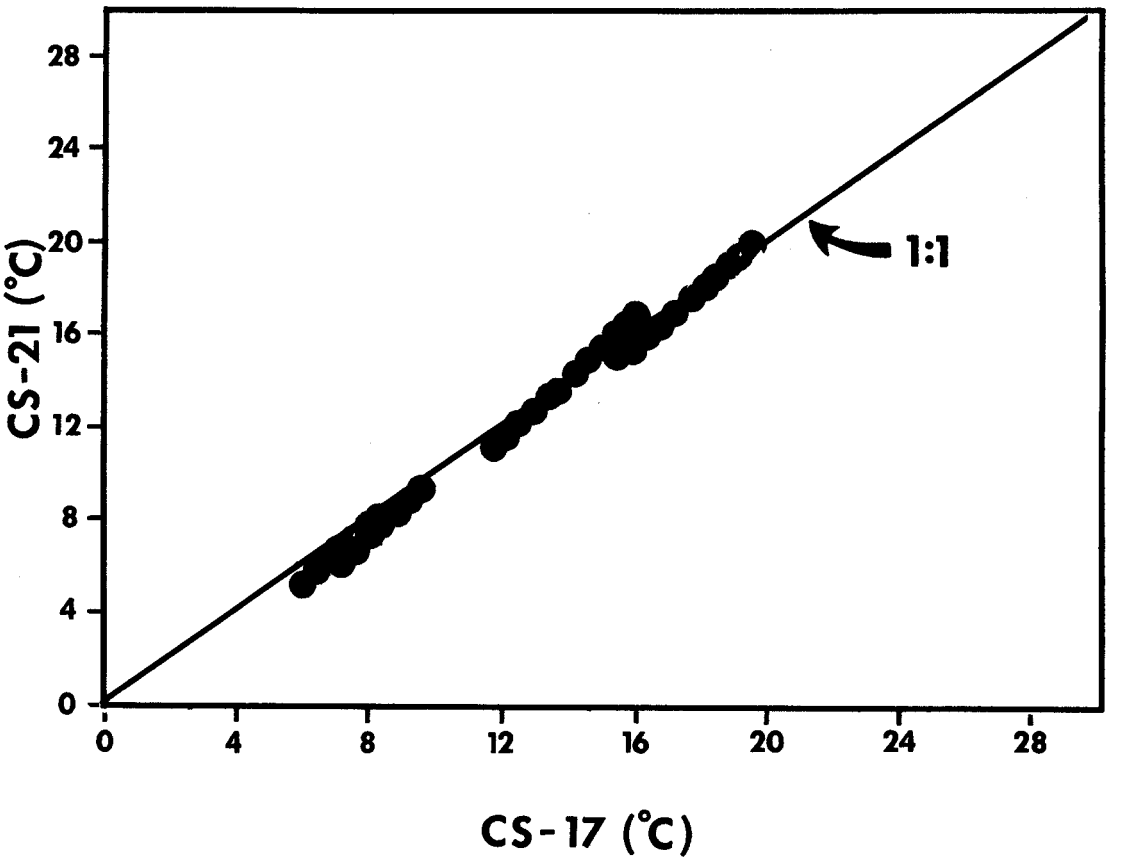


Figure 1—Comparison of litter-soil temperature predictions using south-facing (WS 2) and north-facing (WS 17) prediction equations.

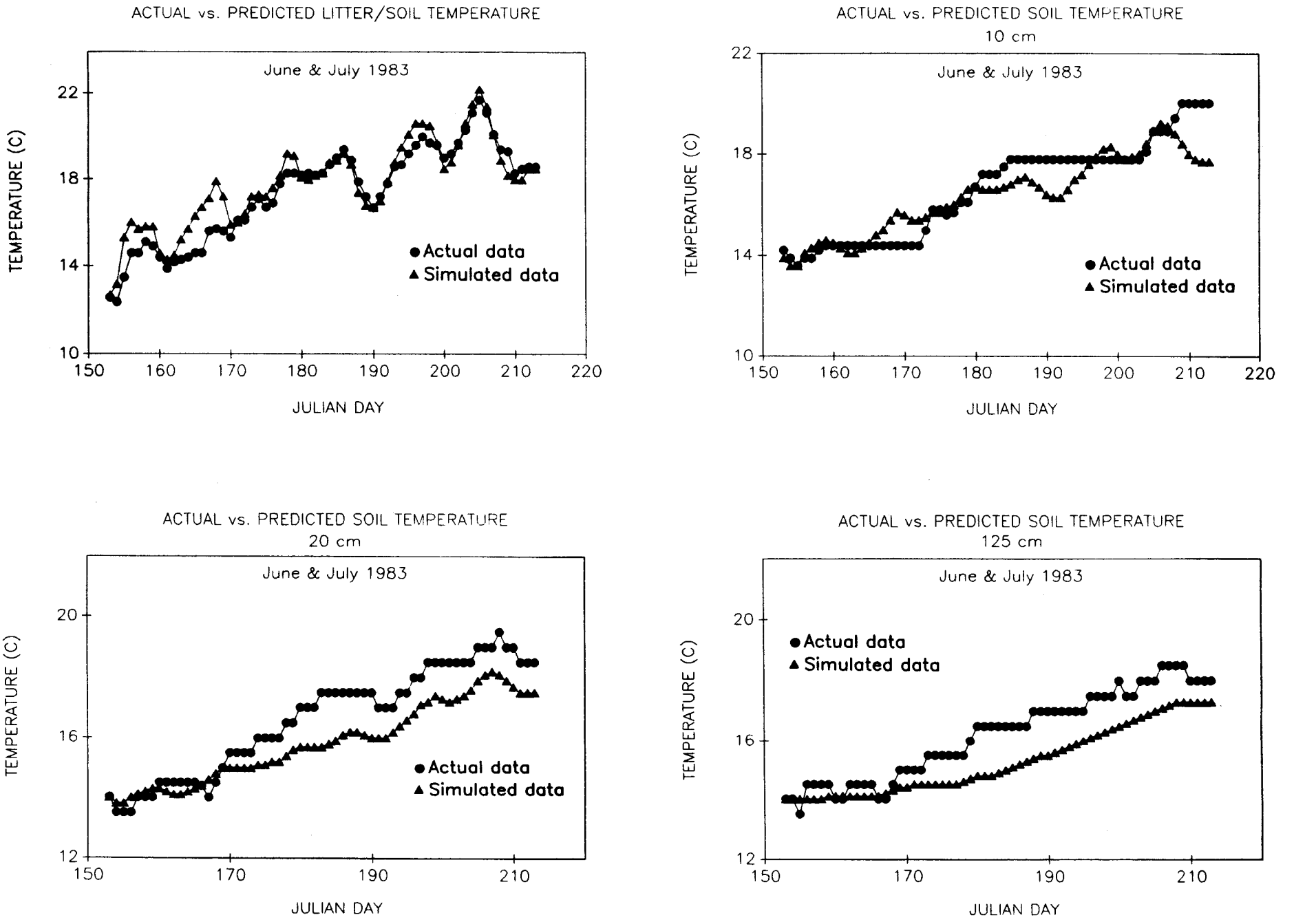
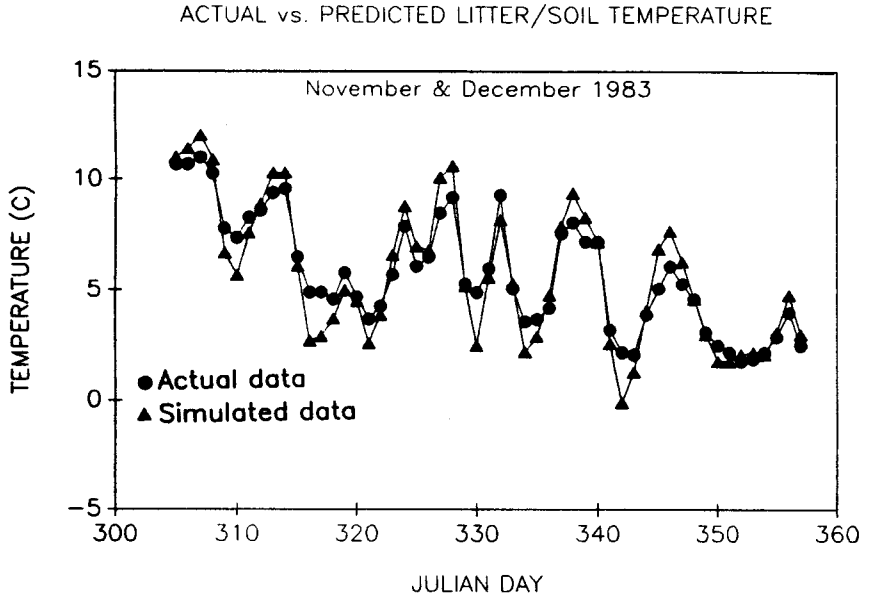
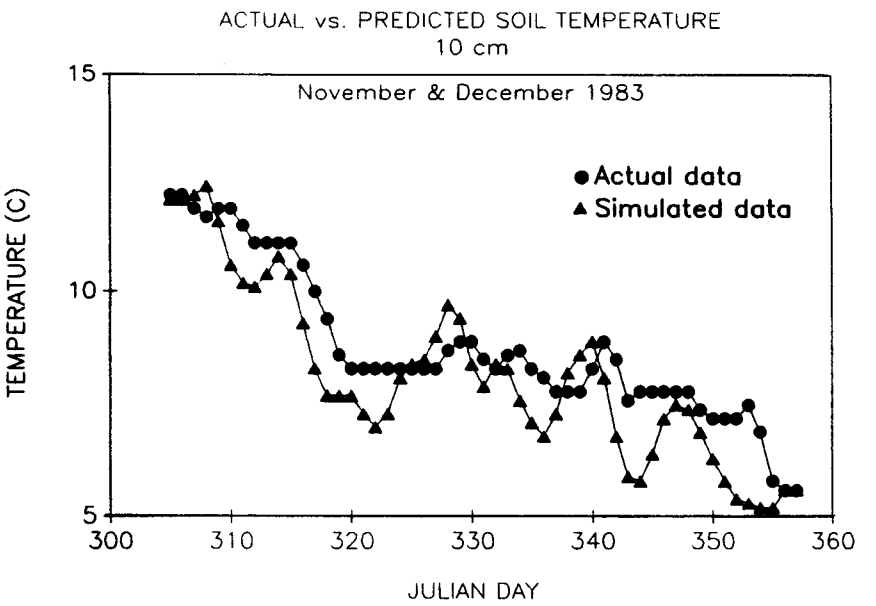
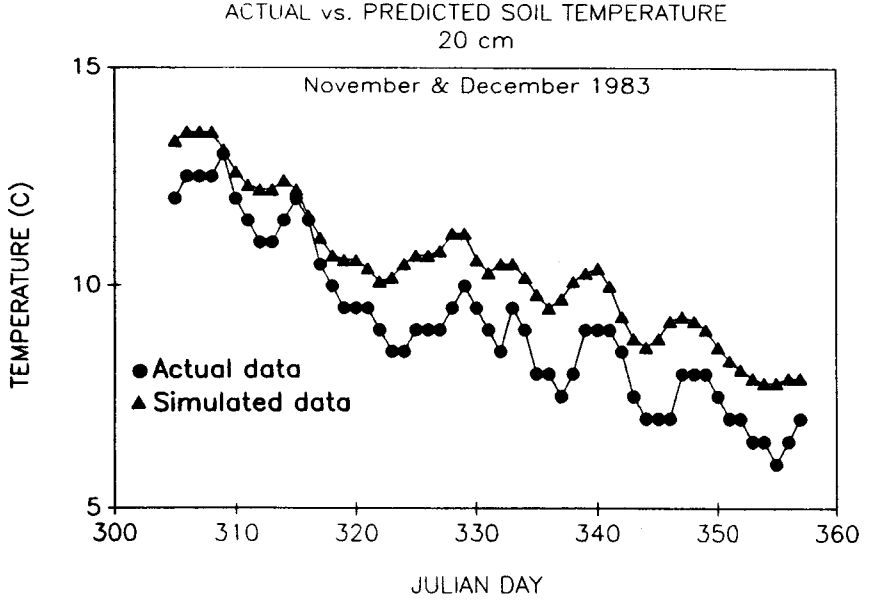


Figure 2—Litter-soil interface and soil temperature simulations for June and July.







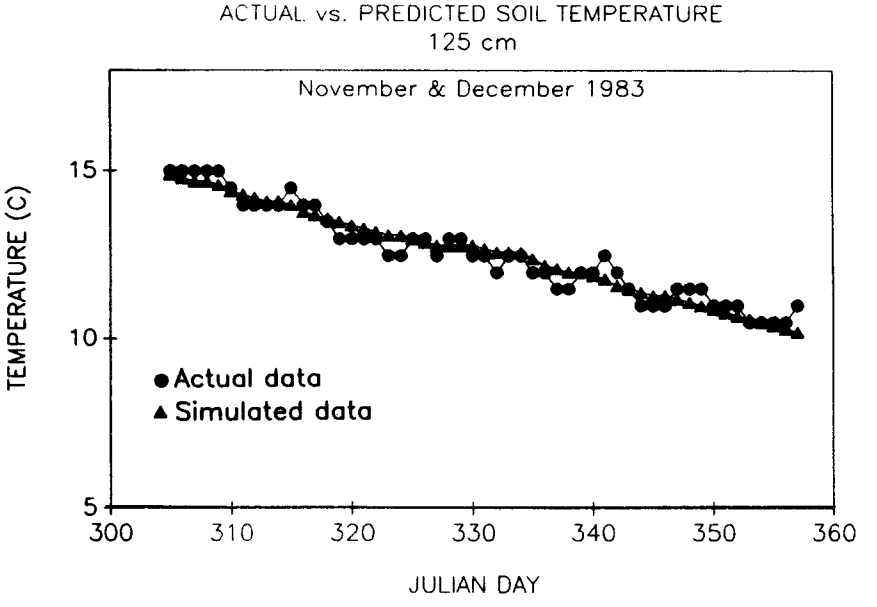


Figure 3—Litter-soil interface and soil temperature simulations for November and December.

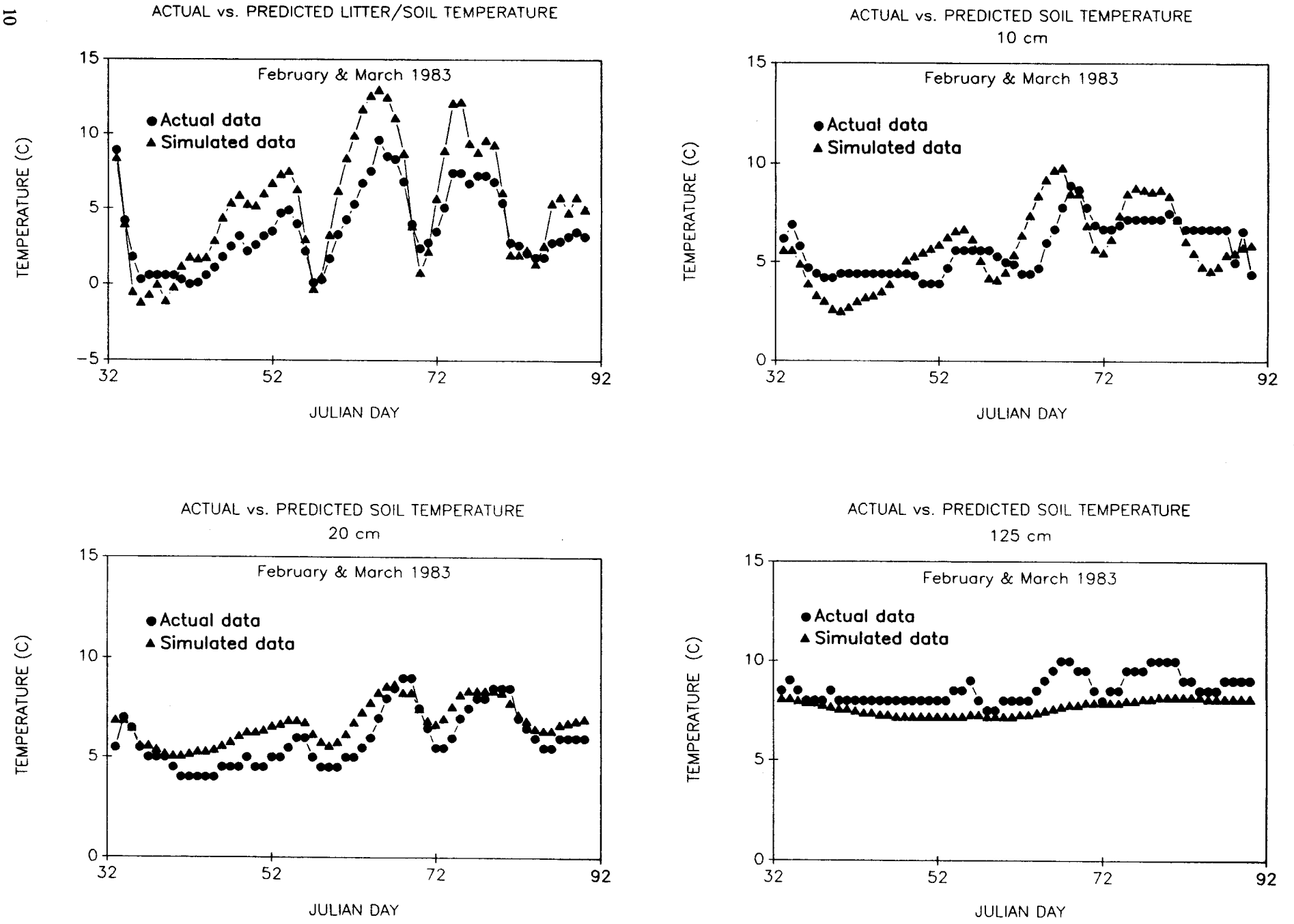


Figure 4—Litter-soil interface and soil temperature simulations for February and March.

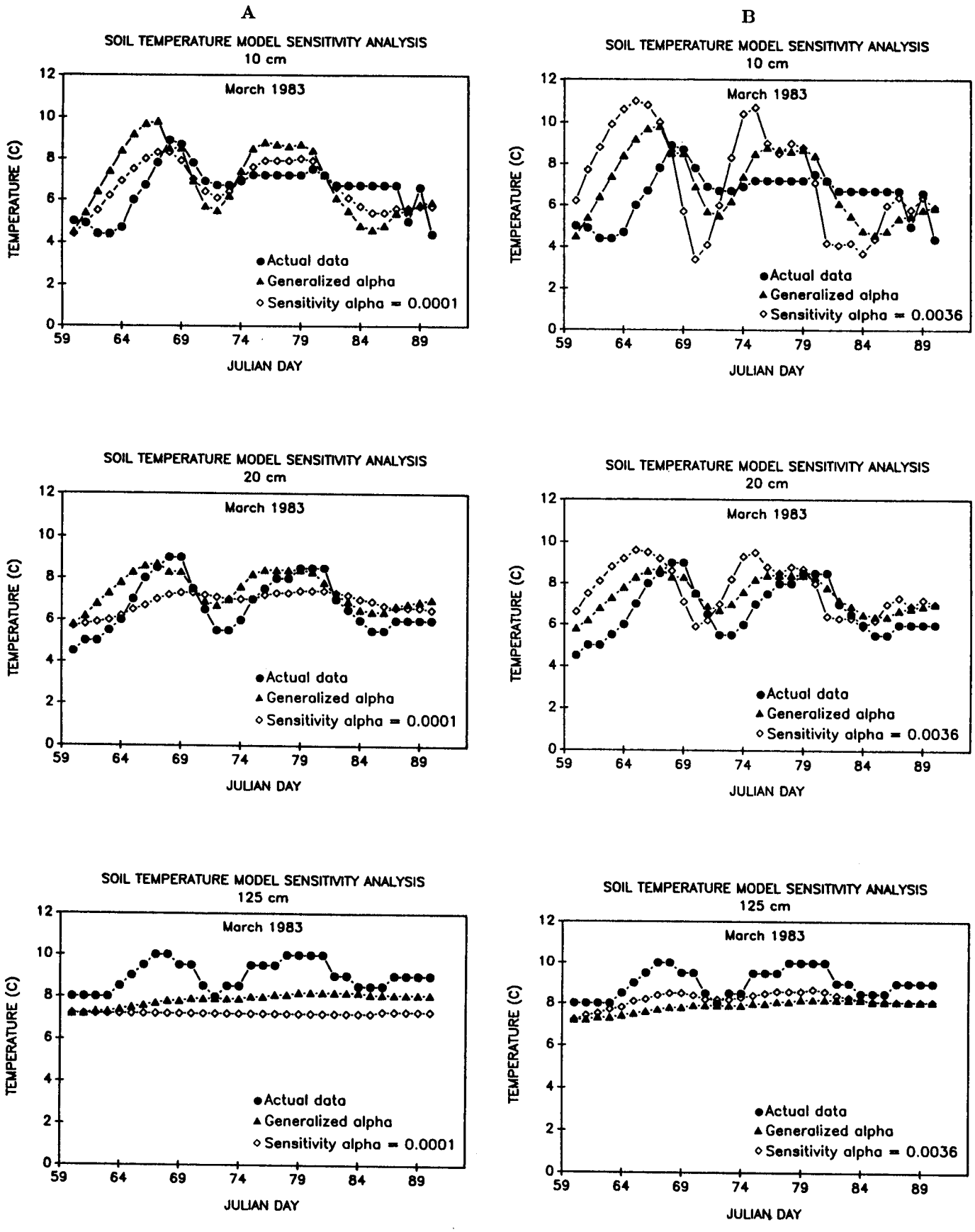


Figure 5—Soil Temperature simulations using α values of 0.0001 (A) and 0.0036 (B).

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KEYWORDS: Computer model, soil heat flow, litter-soil interface temperatures, seasonal variation, hourly soil temperature, BASIC.

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