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Modeling Soil Temperature of Sloped Surfaces by Using a GIS Technology†

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ABSTRACT

Spatial patterns of soil temperature on sloping lands are related to the amount of solar irradiance at the surface. Since soil temperature is a critical determinant of many biological processes occurring in the soil, an accurate prediction of soil temperature distribution could be beneficial to agricultural and environmental management. However, at least two problems are identified in soil temperature prediction over natural sloped surfaces. One is the complexity of converting solar irradiances to corresponding soil temperatures, and the other, if the first problem could be solved, is the difficulty in handling large volumes of geo-spatial data. Recent developments in geographic information systems (GIS) provide the opportunity and tools to spatially organize and effectively manage data for modeling. In this paper, a simple model for conversion of solar irradiance to soil temperature is developed within a GIS environment. The irradiance-temperature conversion model is based on a geophysical variable consisting of daily short- and long-wave radiation components calculated for any slope. The short-wave component is scaled to accommodate a simplified surface energy balance expression. Linear regression equations are derived for 10 and 50 cm soil temperatures by using this variable as a single determinant and based on a long term observation data set from a horizontal location. Extendability of these equations to sloped surfaces is tested by comparing the calculated data with the monthly mean soil temperature data observed in Iowa and at 12 locations near the Tennessee - Kentucky border with various slope and aspect factors. Calculated soil temperature variations agreed well with the observed data. Finally, this method is applied to a simulation study of daily mean soil temperatures over sloped corn fields on a 30 m by 30 m resolution. The outputs reveal potential effects of topography including shading by neighboring terrain as well as the slope and aspect of the land itself on the soil temperature.

Key words: soil temperature, slope and aspect, precision farming, site specific farming, geographic information system.

Growing interest in so-called 'site specific farming' has increased the demand for precise classification of spatial resources distributed within agricultural ecosystems (Petersen et al., 1995). Soil temperature is one of the primary resources for the simulation of plant growth and development (Hodges & Evans, 1992), soilborne insect development (Kluender et al., 1993), and nitrification and denitrification rates of applied ammonia (Killorn & Taylor, 1994). If there exists any spatial variation of soil temperature over a cropland, prediction of that variation will be beneficial in many applications. Theoretically and empirically, soil temperature distribution over a nonhorizontal surface cannot be represented by a single point measurement. The soil temperature is influenced by incident solar energy. The deviation of solar irradiance for a sloped surface from that of horizontal surface is determined by slope and aspect of the surface.

There are numerous papers on soil temperature prediction. Soil temperature models may be grouped into three categories depending on the strategies they incorporate. One is a numerical simulation approach, which solves a heat conduction equation with hourly or shorter time intervals and with small spatial scales (Mahrer, 1982; Lascano & van Bavel, 1983; Benjamin et al., 1990; McCann et al., 1991; Bonan, 1991; Yin & Arp, 1993). Some of these are capable of simulating the effect of soil surface shape (i.e., microrelief caused by tillage practice) on soil temperatures (Mahrer, 1982; Benjamin et al., 1990; Bonan, 1991). Because input requirements for this group are generally high, it is not suitable for operational soil temperature prediction on a large area basis. The second group of studies is purely empirical. They are based on simple regression or harmonic analysis and synthesis (Toy et al., 1978; Meikle & Treadway, 1981; Gupta et al., 1982; Dwyer & Hayhoe, 1985; Kluender et al., 1993). Most of them simulate daily soil temperatures from daily air temperatures so that data requirements are generally low. However, they cannot be used in soil temperature simulation for sloped surfaces because they lack topographic variables. A third group may be called "semi-empirical" because the soil temperature models in this group use some physical principles but are simplified by empiricism (Parton, 1984; Kemp et al., 1992; Potter & Williams, 1994). They can be used to simulate soil temperatures for hourly to daily time scales with greatly reduced input requirements compared with the first

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group. But neither the soil microrelief nor the larger scale terrain effects on soil temperature can be simulated by this group of models because they do not consider any effects of topography on soil temperature.

No existing soil temperature model was found suitable for a large-scale operational prediction of absolute value or for deviation of soil temperatures over a sloped surface compared with over horizontal surface. For a model to be operational, the output should cover an area large enough to accommodate land management practices but stay on daily or shorter time interval to be relevant to most agricultural practices, while keeping input requirements minimal and readily available. Once a reasonable soil temperature model for any slope is formed, another problem must be solved for practical applications. Since land surfaces can be considered as an inhomogeneous continuum from the viewpoint of topography, any influence of neighboring terrains on irradiance, and resultant effects on soil temperature must be taken into account. Effects of shading could be substantial for croplands in mountainous area, for example. Hence, the model should incorporate a spatial analysis tool to avoid this limitation. Geographic information systems (GIS) technology provides a tool to encode, spatially organize, manipulate, analyze, and present model input and output data. This technology has been used extensively in studying environmental and, more recently, agricultural processes (Petersen et al., 1995).

This study explains a simple method for estimating daily soil temperature distribution for sloped surfaces by using a GIS technology.

MODEL DESCRIPTION

Soil temperature is determined by the soil surface energy balance and by soil thermal characteristics as influenced by soil water and soil physical properties. Observed soil temperature represents a sensible heat flux of the soil resulting from the surface energy balance and thermal diffusivity of that soil, the latter being determined largely by soil physical characteristics (Hillel, 1980). Assuming little variation in soil physical characteristics across the area averaged over a long time period, the long-term trend of soil temperature is determined by the surface energy balance, which allocates the absorbed net radiant energy into sensible heat and latent heat. Soil heat flux is usually estimated by subtracting these two terms from net radiation. Hence the variation from long-term average for subsoil temperature is related to the sum of the sensible and the latent heat at the surface.

The model holds all input parameters constant except net radiation. The net radiation is influenced by the locality, season, and the surface slope and aspect. The GIS technology could be applied to larger areas such that air temperature, precipitation distribution, etc. could not, realistically, be considered uniform.

Sharratt et al. (1992) simulated net radiation over sloped surfaces based on energy conservation and geometry. They found daily net irradiance to be higher on south-facing slopes than horizontal lands, which is consistent with the higher observed soil temperatures of south slopes in ridge tillage experiments (Shaw & Buchelle, 1957; Burrows, 1963). They also calculated lower net irradiance on west-sloping surfaces. But Radke (1982) reported consistently higher soil temperatures on west sloping surfaces. This would be anticipated by the consideration of the temporal and spatial distribution of solar radiation and the temporal air temperature distribution that normally results in air temperature reaching its peak value some time after midday.

This model is based on the assumption that air temperature is uniform across a field and is not significantly influenced by the slope and aspect of the terrain. Second, it is assumed that the soil temperature on horizontal terrain is determined by incident radiation and the temperature of the air. Soil temperature, as influenced by slope and aspect, is a function of the geometric relationship of incident radiation to slope and aspect.

Formulation of variable

We propose a synthetic geophysical variable (K_j), which is a combination of theoretical solar and long-wave irradiances on any slopes. It can be written as

$$K_j = A \sum_{i=1}^{24} B_i S_i + L_j \text{ (for } i=1 \text{ to } 24, j=1 \text{ to } 365) \quad (1)$$

Where

A is an empirical constant simulating the fraction of total solar irradiance to soil heat flux.

B_i is an empirical constant simulating the differential effect of hourly solar irradiance on soil temperature.

S_i is the short-wave irradiance for ith solar hour of jth day.

L_j is the long-wave irradiance for jth day.

Each component is explained in detail, and the calculation procedure used in this study follows.

1. S_i

Total short-wave irradiation of any slope at the surface of the earth with an upward- or downward-facing plane surface is given by

$$S_i = Sb_i + Sd_i + Sr_i \quad (2)$$

where Sb_i is the direct beam, Sd_i is the diffuse, and Sr_i is the reflected solar irradiances on the surface at time i. In practice, Sb_i and Sd_i may be measured directly. Under most conditions, measured values should be used in preference to equations 3 and 4.

Direct beam solar irradiation of slope was calculated by following the derivation by Radke (1982).

$$Sb_i = S0 * TAU^{1/SIN(alt)} * [COS(alt)\ COS(dazi)\ SIN(slp) + SIN(alt)\ COS(slp)] \quad (3)$$

In this formula, S0 is the solar constant, TAU is the transmittance of the atmosphere, alt is the solar altitude angle at time *i*, dazi is the difference between the slope aspect and the solar azimuth at time *i* (both of them measured from south, i.e., east is $-\pi/2$ and west is $+\pi/2$), and slp is the inclination of the surface. A common value for S0 is 1,360 W/m^2, i.e., 4.896 MJ m^{-2} hr^{-1}, and we used this value for S0. Commonly observed values of TAU vary from 0.4 to 0.8 depending on sky condition. We used 0.8 assuming a Rayleigh sky condition (Gates, 1980).

Assuming an isotrophic sky radiation, diffuse irradiation component was calculated by following Gates (1980).

$$Sd_i = S0 * [0.271 - 0.294 * TAU^{1/SIN(alt)}] * SIN(alt) * COS^2(slp/2) \quad (4)$$

The last term in this formula, $COS^2(slp/2)$, is the so-called 'sky view factor'. Calculation of diffuse irradiation on a slope is based on the direct beam solar irradiance on horizontal surface. The second term, within brackets $0.271 - 0.294 * TAU^{1/SIN(alt)}$, is an empirical function for the atmospheric transmittance of scattered and/or reflected light.

Reflected irradiation was also calculated by following Gates (1980).

$$Sr_i = S0 * ALB * [0.271 + 0.706 * TAU^{1/SIN(alt)}] * SIN^2(slp/2) \quad (5)$$

In this equation, ALB is the soil surface albedo; 0.2 was used in the examples described. The last term of this equation, SIN^2 (slp/2), defines the area illuminated by ground-reflected irradiation on a unit area basis, i.e., one subtracted by the sky view factor. All radiation terms are in units of MJ/m^2.

2. B_i

Air is usually colder at sunrise than at sunset. Accordingly, equivalent insolation in the morning will increase soil temperature to a lesser degree than will the afternoon sun. Additionally, soil may be more moist in the morning hours than in the afternoon, and more radiation will be used to evaporate soil moisture, retarding air temperature and soil temperature increase in the morning. Since soil temperature is proportional to the thermal gradient between the surface and the measurement depth, morning soil temperatures will remain low as long as the air temperature remains low even though the solar irradiance is substantial. During the afternoon, soil surface moisture may be depleted and air temperature elevated; thus, the same amount of net radiation (or total solar irradiance) will contribute more energy to heating the soil at some depth because the evaporative and the convective loss of energy are diminished. The direct heating of the top few centimeters of soil by solar irradiance may also be greater for drier soils.

To make the problem simple, we assumed the relative contribution of solar energy to soil temperature at a given time of day is linearly related to air temperature of that time. This weighting procedure is necessary for taking into account the apparent synergism between solar irradiance and air temperature, e.g., higher soil temperature for a west-facing slope than for an east-facing one. Assuming a sinusoidal air temperature trend with the maximum occurring at 1330 true solar time (TST) for each day, an index ranging from 0.1 (0130TST) to 1 (1330TST) was assigned to each hour.

$$B_i = 0.55 + 0.45\ COS(\pi/12\ (i - 13.5)) \quad \text{(No units)} \quad (6)$$

Actual values for daytime index will vary from around 0.5 to 1.0 according to this formula, but the exact value for the lower boundary depends on the day of year. Hence, the potential effect of solar energy at 1330TST on increasing soil temperature will be approximately twice as large as that at sunrise. This formula implies that solar irradiance in the morning is less effective in increasing soil temperatures than is solar irradiance in the afternoon.

3. *A*

Only a portion of incident solar irradiance is absorbed by the soil. The irradiance absorbed will contribute to latent and convective flux as well as to soil heat flux. When the annual march of soil heat flux on bare dry soils is considered, the approximate daytime soil heat flux may be of the order of 10 to 20% of total solar radiation (Oke, 1987). Although the value will vary temporally as well as spatially, we used a fixed value of 0.2 for each day.

4. L_j

Daily long-wave irradiation received at the surface is strongly dependent on air temperature (Gates, 1980) and may be approximated from seasonal air temperatures. The range was derived from daily minimum and maximum temperatures observed in the Midwest (i.e., -18 to 37℃). For simplicity, the seasonal trend was considered to be described by a cosine function:

$$L_j = 25 + 15\ COS(2\pi/365(j - 204)) \quad \text{(Unit: MJ/m}^2\text{)} \quad (7)$$

We assumed no difference in L_j values between horizontal and sloped surfaces. This assumption is logical if long-wave radiation is isotropic and there are no significant view factor contribution differences across the terrain described in the model. Direct measurements of incident long-wave radiation, when available, should be used in place of equation 7.

Deriving the relationship between *K* and soil temperature

Weekly climatological normals of soil temperature at several depths are available for the Agronomy Farm of Iowa State University in Ames, Iowa (Elford and Shaw, 1960). Weekly mean values of K were calculated for a horizontal surface at 42N latitude, which corresponds to the geographic location of Ames. There was a high correlation between the two variables, and we derived a set of regression equations. When soil temperatures at the 10 cm depth were regressed to K, a simple equation, $T_{soil} = 0.99K - 15.44$, explained nearly 99% of variations in weekly normal soil temperatures for the whole season. When the 52 weeks were divided into two 26-week half years, representing warming and cooling halves of the year, slightly different linear equations were derived for each half year, improving the values of both r^2 and F. For soil temperatures measured at the 50 cm depth, different curvelinear equations were derived for the warming half (Feb. 1 to July 31) and the cooling half (Aug. 1 to Jan. 31) of the year, respectively. The equation for warming half is

$$T_{soil} = 0.0081K^2 + 0.24K - 5.57 \ (r^2 = 0.9976),$$

and that for cooling half is

$$T_{soil} = -0.0077K^2 + 1.11K - 12.55 \ (r^2 = 0.9984).$$

When weekly normal soil temperature data for Ames were reconstructed using these regression equations, they showed a close fitting with the original data (Fig. 1). Because effects of snow cover are not considered, there is less agreement with observed data during winter season.

Model verification

We combined the hourly K calculation routine with the

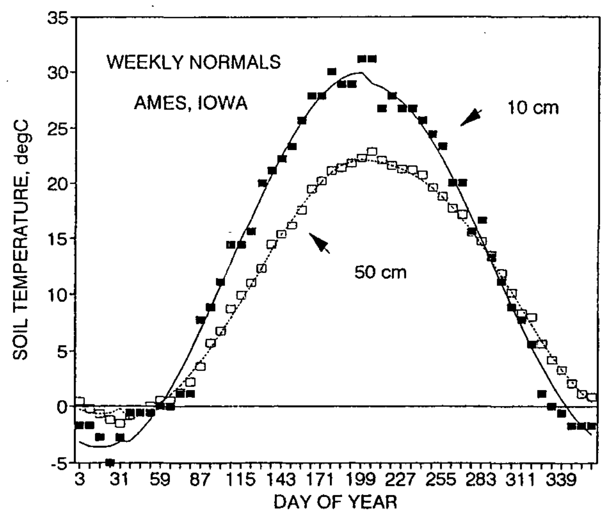

Fig. 1. Weekly normal soil temperatures, 10 and 50 cm depth, at Ames, Iowa, based on observations (squares) and on regression equations (lines).

K-soil temperature relationship to formulate a soil temperature model for sloped surfaces. The model was run for several combinations of slope and aspect under typical winter, summer, and spring conditions, respectively, to show the integrity of solar radiation calculation and to compare K values among various slopes. Established physical formulas were used to calculate solar radiation components in this study, and the results were consistent with existing reports (Radke, 1982; Sharratt et al., 1992). Figure 2 shows a sample calculation of hourly solar irradiances and hourly K values (solar irradiance associated with B_i before summed up and multiplied by A) for southeast- and southwest-facing 30 degree slopes at 42N latitude on April 11. Although the amount of solar irradiance on both surfaces are the same, K values are greater on southwest-facing slope because of the time/temperature weighting imposed by equation 6. For all the seasons tested, southeast slope starts earlier accumulation of solar irradiance, but daily sums of K are always higher on southwest slopes. A higher K value results in a higher soil temperature which is consistent with observations on soil microreliefs by Radke (1982).

MODEL VALIDATION

Because the objective of this model development is a prediction of soil temperatures over nonhorizontal croplands, extensive measurements of soil temperatures are required to fully test the validity of this model.

Unfortunately, few data are available for this purpose. Although there were no data for such a full validation of this model, an observation study reported by Franzmeier et al. (1969) was sufficient to provide some spatial vali-

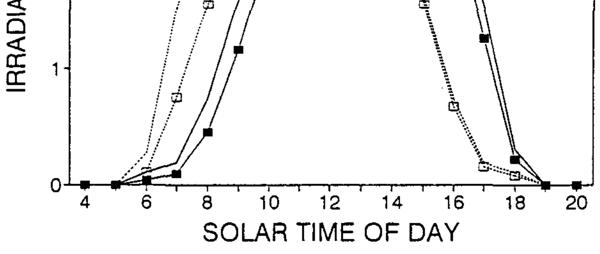

Fig. 2. Model calculated hourly solar irradiances (S) and K values for southeast- and southwest-facing slopes on April 11 (latitude = 42N, slope inclination = 30 degrees).

dation. They measured 50 cm depth soil temperatures at 12 locations near Kentucky-Tennessee border with various slope and aspect values for a full year period starting fall of 1963. The slope gradients varied from 36% to 62% and the aspects were divided into south and north with a little variation.

Calculated soil temperatures by the model were compared with the observed values of Franzmeier et al., (1969). Our model should have used a *K*-soil temperature relationship relevant to the Franzmeier data, but it was not possible to get appropriate data for that region. Hence, the viewpoint of model validation was put on comparison of relative differences rather than on comparison of absolute values among observation points. The only adaptation of the original model to Franzmeier data was changing the latitude from 42N (Ames, Iowa) to around 36N (Tennessee-Kentucky border).

SAMPLE APPLICATION TO SLOPING CORNFIELDS

Spatial variations of 10cm daily soil temperatures were calculated for a real land surface in Iowa using this model. A 1.6 km by 1.6 km rectangular area, about 10 km southeast of Ames was chosen for this study because it is close to Ames. The K-soil temperature relationship is known for this site, and it has a relatively diverse topography. Overall, the terrain is gently sloping from the northeast to the southwest, with a stream at the southwest end making a more diverse topography.

Elevation contours were digitized from a relevant 1:24, 000 USGS topographic map to create an ARC/INFO line coverage (ESRI, 1994). The contour lines were converted first to a TIN (Triangulated Irregular Network) file by the ARC/INFO function "createtin", and next to a lattice file by the "tinlattice" ARC/INFO command. The lattice file consists of a 53 by 53 lattice matrix, each grid cell representing the elevation of the lattice point. Thus, each grid cell is a 30 m by 30 m square. Using the ARC/INFO GRID module (ESRI, 1992), the slope and the aspect of each grid cell relative to neighboring cells were calculated and stored as grid files, respectively. Estimated slope range was horizontal to 11.8 degrees, and the mean aspect was −21.6 degrees (South-Southwest). Also, hillshades caused by neighboring cells were calculated by a GRID function "hillshade" and stored as a temporary grid file for each time of day. If any grid cell is shaded by neighboring cells, this cell receives no direct beam radiation even though the calculated solar altitude is above the horizon for that cell.

Full features of our model were incorporated into ARC/INFO environment by writing an AML (ARC/INFO Macro Language) program (ESRI, 1994). The AML program was run to calculate and display soil temperature for each cell. The spatial distribution of soil temperatures were created for January 1, April 11, July 20, and October 27.

RESULTS AND DISCUSSION

Figure 3 shows the comparison of 50 cm soil temperatures calculated by our model for slope and aspect cases matching those reported by Franzmeier et al. (1969). The model underestimates, as was expected, soil temperatures for winter and spring seasons from November to April of the next year. Also, there is a slight overestimation in midsummer months. This deviation is presumably due to the difference in seasonal pattern of soil temperatures between the Tennessee - Kentucky border area where observations were made and central Iowa where the *K*-soil temperature equation was developed. We expect a greater annual range of soil temperature in Iowa than in the southern states.

The model performs well in predicting temperature differences between locations. The model predicts the absolute differences and the relative trends among locations accurately in most cases. Franzmeier et al. (1969) observed more pronounced differences in soil temperature among locations in winter months than in summer. The model predicted this season-dependent differential effect of topography.

In July and August, however, there is a deviation from observed values, especially for the right part of Fig. 3. The six observations on the left half of the figure are from Kentucky, and those on the right half are from Tennessee. Both parts are located about 50 km north-south from each other, and the model predicted a slightly higher temperature for the southern part because latitude is the only geographical input requirement for the model. But the observed summer 1964 temperatures

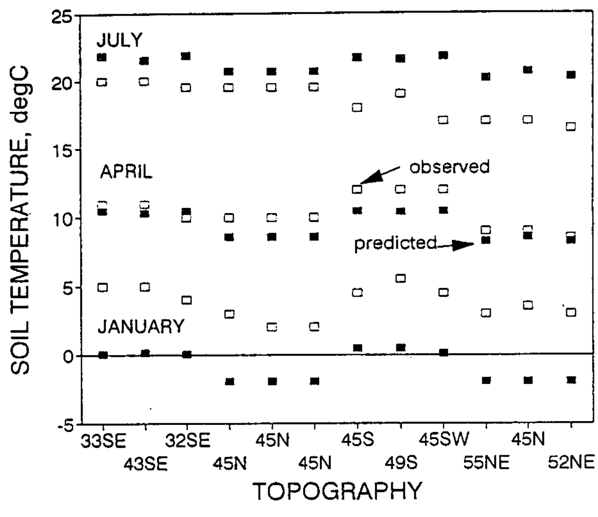

Fig. 3. Comparison of monthly mean soil temperatures calculated by the model with the observed data from Franzmeier et al. (1969) for January, April and July. Each X axistic values consist of slope and aspect (e.g., 45SE = southeast facing 45 degree slope).

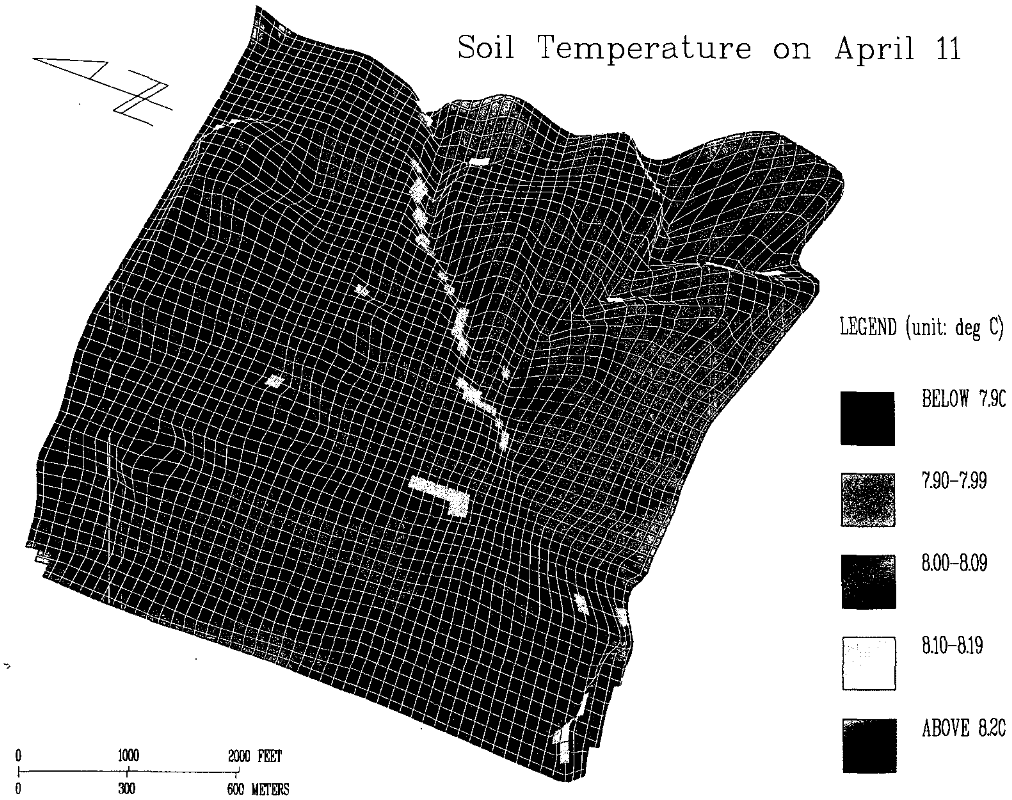

Fig. 4. Relief depiction of the spatial distribution pattern of 10 cm soil temperatures for April 11 based on the model calculation. Each grid cell represents a 30 m by 30 m square land area.

were lower at the southern locations. The model is based largely on a clear sky solar irradiance of sloping surfaces and neglects any effects from varying sky conditions or from precipitation. Interregional variations in rain and cloud amounts during the summer might contribute to deviation from predicted values.

Figure 4 shows the simulated temperature pattern draped over the land surface. Each cell represents the calculated daily average soil temperature at 10 cm depth based on the slope and aspect of 30 m by 30 m land surface segments. The simulated soil temperature pattern reveals not only the theoretical effect of slope and aspect, but also the potential shading effect of neighboring terrains. Hence, the lower temperatures are found at the northward slopes of deeper valleys.

According to the model calculation, daily averages of soil temperature in this area varied from 7.8 to 8.3℃ on April 11 in a 'normal' year. This amount of spatial variability might be negligible compared with diurnal ranges commonly found in this season of year, but the daily accumulation from this pattern, i.e., heat units or growing degree days, could make a significant spatial variation and cause differential responses of biological activities over a season.

We have suggested a feasible method to express topographical effects on soil temperature by using a GIS technology. This method might be applied to provide spatial information on soil temperature, one of the important natural resources for site-specific farming. Because the model is run under a GIS environment, further analysis can be done using the built-in GIS functions on the output data.

Performance of this prototype soil temperature simulator shows a prospect of developing more realistic models for soil temperature. Although the current method is applicable exclusively to prediction of daily normals, the methodology might be extended to accommodate day-to-day variations in soil temperature, e.g., consideration of actual solar and thermal regimes for a specific area. Access to local weather data is easier than in the past because of operational automated weather stations and data communication techonology. Utilization of near real-time data as well as historical data will make this task more feasible. Operationally, Si could be derived from radiation measurements rather than being simulated from the solar constant as expressed above.

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