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# A GEOMETRIC SOLAR RADIATION MODEL AND ITS APPLICATIONS IN AGRICULTURE AND FORESTRY*

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## ABSTRACT

Incoming solar radiation (insolation) is fundamental to most physical and biophysical processes because of its role in energy and water balance. We developed a geometric solar radiation model, the Solar Analyst, which calculates insolation maps from digital elevation models (DEMs). Highly optimized algorithms account for influences of the upward–looking viewshed, surface orientation, elevation, and atmospheric conditions. The Solar Analyst is a convenient effective tool with diverse applications in agriculture and forestry. Herein we focus on its application for spatial interpolation of soil temperature measurements over complex topography at landscape scales. Existing interpolation techniques generally apply only at continental or broad regional scales and do not capture the high variation of finer scales. In our field study in the vicinity of the Rocky Mountain Biological Laboratory, average soil temperature was strongly correlated with insolation and elevation. While daily minimum temperature was negatively correlated with elevation, daily temperature change (maximum minus minimum) was positively correlated with daily insolation. We generated daily minimum and maximum soil temperature maps based on regression analyses. Residual variation was explained by factors such as vegetation cover. This application demonstrates the importance of characterizing spatial and temporal variation of insolation for studies of energy and water balance.

## 1.0 INTRODUCTION

**Importance of Spatial Insolation Models:** Insolation, through its influence on the energy and water balance at Earth's surface, affects such processes as air and soil heating, evapotranspiration, photosynthesis, winds, and snow melt (Geiger 1965, Gates 1980, Dubayah and Rich 1995, Rich *et al.* 1995). Accurate insolation maps at landscape scales are needed for many applications in agriculture and forestry. At landscape scales, topography is the major factor modifying the distribution of insolation. Variability in elevation, surface orientation (slope and aspect), and obstruction by surrounding topographic features create strong local gradients of insolation. For most geographical areas accurate insolation data are not available. Furthermore, simple interpolation and extrapolation of point measured insolation are not feasible because of high topographic heterogeneity. In contrast to the high cost of building and maintaining insolation monitoring stations, spatially–based solar radiation models provide a cost–efficient means for characterizing the spatial and temporal variation of insolation. The SolarFlux model (Hetrick *et al.* 1993a, 1993b, Rich *et al.* 1995) and other similar models (Kumar *et al.* 1997) simulate the influence of shadow patterns on direct insolation at discrete intervals through time. These models were developed for the ARC/INFO GIS platform (ESRI, Redlands, CA), and have been widely used by researchers of diverse fields. But these models were limited by the computation speed of Arc Macro Language (AML), simplistic diffuse calculations, and availability only for use with high–cost GIS software. A new generation model is needed to provide better accuracy, faster speed, more rigorous diffuse calculations, improved flexibility, and broad availability.

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**TopoView and the Solar Analyst:** Based on this need, we developed the TopoView model, which calculates insolation maps, including both direct and diffuse solar radiation, from digital elevation models (DEMs). We ported it as the Solar Analyst, an ArcView GIS extension (ESRI, Redlands, CA), which provides an expanded user interface and calculation capabilities. The theory and algorithms of TopoView and the Solar Analyst are described in detail by Fu and Rich (1999a, 1999b, http://www.hemisoft.com). In essence, they use a new generation algorithm (Rich 1994) that generates upward–looking viewsheds based on DEMs, and uses these viewsheds to calculate incoming direct and diffuse radiation from each sky direction. Solar Analyst has the following advantages over previously developed models:

- **Versatile output:** calculates direct, diffuse, global radiation, & direct radiation duration, skyview factor, sunmaps and skymaps, and viewsheds;
- **Simple input:** requires only DEM, atmospheric transmittivity, and diffuse proportion (latter two parameters calculated from nearby weather stations or using typical values);
- **Improved flexibility:**
    - ➢ calculates insolation for any specified period (instantaneous, daily, monthly, weekly …);
    - ➢ calculates insolation for any region (whole DEM, restricted areas, or point locations);
    - ➢ allows specification of receiving surface orientation (from DEM, field survey, or orientations of surfaces such as sensors or leaves) and height offsets for ground features;
- **Fast and accurate:** uses advanced viewshed algorithm for calculations; accounts for viewshed (sky obstruction by near–ground features), surface orientation, elevation, and atmospheric conditions; calculation engine implemented in C++ library format and dynamically loaded;
- **User friendly:** user interface implemented using ArcView Dialog Designer and ArcView Avenue; extension benefits from ArcView's mapping, query, graphing, & statistics functions;
- **Broad accessibility**: based in ArcView; does not require expensive, high–end GIS software;
- **Programmable**: adds new object–orientated components, including new classes and instance requests, to ArcView Avenue; improves user efficiency by allowing task automation; permits development of custom models (e.g., energy balance and water balance models) by programming the Solar Analyst along with Avenue or other model libraries.

**Studies of Microclimate in Complex Terrain:** As part of an ongoing project concerning vegetation patterns and climate change in the Rocky Mountains we require detailed maps of microclimate, including temperature. In this topographically diverse area, temporal and spatial variation of insolation must be considered when constructing high-resolution temperature maps.

## 2.0 APPLICATION IN SPATIAL INTERPOLATION OF TEMPERATURE DATA OVER COMPLEX TOPOGRAPHY AT LANDSCAPE SCALES

### 2.1 Background

**Spatial Variation of Temperature:** Air Temperature and soil temperature, along with water availability and soil, are key factors for agriculture and forestry systems. Under many situations temperature is the factor that determines which crops or trees can be grown in a given area, seed germination, growth rates, rates of maturation or ripening, and yield.

At a global scale, the major pattern of vegetation is defined by latitudinal gradients. At continental and regional scales, elevation modifies the latitudinal gradients according to adiabatic lapse rates. Because of the large area and coarse spatial resolution of these scales, temperature regimes appear smooth and simple interpolation can be adequate for characterizing patterns. At a landscape and local scales, temperature patterns are strongly influenced by fine–scale insolation variation and microsite factors (vegetation, soil properties, wind…). Innumerable researchers have observe high temperature variation in areas of high topographic relief. For example, Holch (1931) found that maximum air temperatures were from 0.5$^{o}$ to 5$^{o}$ C higher on south versus north–facing slopes. Cottle (1932), in his study of vegetation in the mountains of Big Bend County, Texas, found that soil temperature at two inch below the surface were about 5$^{o}$ to 10$^{o}$ C higher on south–facing versus north–facing slopes. Wilson (1970) documented differences air temperature differences (mean weekly maximum) of 5$^{o}$ C in spring and 1.8$^{o}$ C in summer for north versus south–facing slopes in forested areas of Mont St. Hilaire, Quebec. Temperature differences for bare ground areas were even larger. More recently, Dixon (1986) in his study of plant distributions in the Rocky Mountains, found that soil temperatures are typically 0.4$^{o}$ to 12.1$^{o}$ C warmer than ambient air temperature, and both air and soil temperature vary significantly with topographic position.

**Interpolation of Meteorological Data:** Characterization of temperature for a study area typically relies upon a series of measurements at discrete locations. Spatial interpolation of these discrete data into a continuous surface is generally the first step for use with other GIS data layers. Remote sensing of surface temperature appears to be a promising technology, however slope and aspect variations in mountainous regions lead to difficulties of data interpretation (Lipton 1992). Researchers have used diverse statistical and geostatistical models to generate temperature surfaces from point sampling locations. The simplest technique uses the nearest measurements and can not capture temperature variation in complex topography. Another simple technique in widespread use examines a set of aspect, slope, and elevation groups, and assumes that temperature within the group are similar (Daubenmire 1956, Ayyad and Dix 1964, Dixon 1986). This method may treat very different landscape positions in similar ways because it neglects differences in sky obstruction by surrounding topographic features. In addition, categories are not continuous and subtle differences between surface orientation are neglected. Trend surfaces, inverse distance weighted interpolation (IDW), thin plate spline, and ANUSPLIN (Hutchinson 1991) all have been used to interpolate temperature measurements over global, continental, and broad regional scales (Collins and Bolstad 1996, Kesteven and Hutchinson 1996). These models, however, assume the underlying surface is smooth and lack the mechanism for use in mountain regions with complex topography. Kriging and surface interpolations of the MT–CLIM model (Hungerford *et al.* 1989, Running and Thornton 1996) can use correlated variables for creating surfaces, they have not been used in landscape scales due to the lack of high resolution insolation data. The problem of interpolating or extrapolating site–specific measurements, including temperature, to obtain landscape scale estimates remains a challenge (Burrough and McDonnell 1998).

Insolation has a direct effect on temperature by adding energy that heats the ground surface. Successful spatial interpolators should not neglect this underlying physical process. The Solar Analyst can generate maps of insolation at high spatial and temporal resolution. We expect that insolation maps will be highly valuable in spatial interpolation and extrapolation of temperature measurements over complex topography.

## 2.2 METHODS

**Study area:** As part of a regional analysis of relations between microclimate and vegetation in the Rocky Mountains, we are examining field measurements and topoclimatic models in the Grand Mesa–Uncompahgre–Gunnison (GMUG) National Forests and other parts of the Gunnison Basin, Colorado, for which detailed vegetation, soil, DEMs, and weather measurements are readily available. This area has dramatic topographic variation. Elevations area range from 1600 m to 4400 m. We obtained over 100 USGS 7.5'/30 m resolution DEMs that cover the entire area. These DEMs will serve as a primary data layer for constructing maps of potential air temperature, soil temperature and soil moisture, and potential evapotranspiration. We obtained weather station data from the National Water and Climate Center. Herein we present some preliminary results for spatial interpolation of soil temperature in the immediate vicinity of the Rocky Mountain Biological Laboratory (RMBL), in the uppermost portion of the Gunnison basin (Fig. 1).

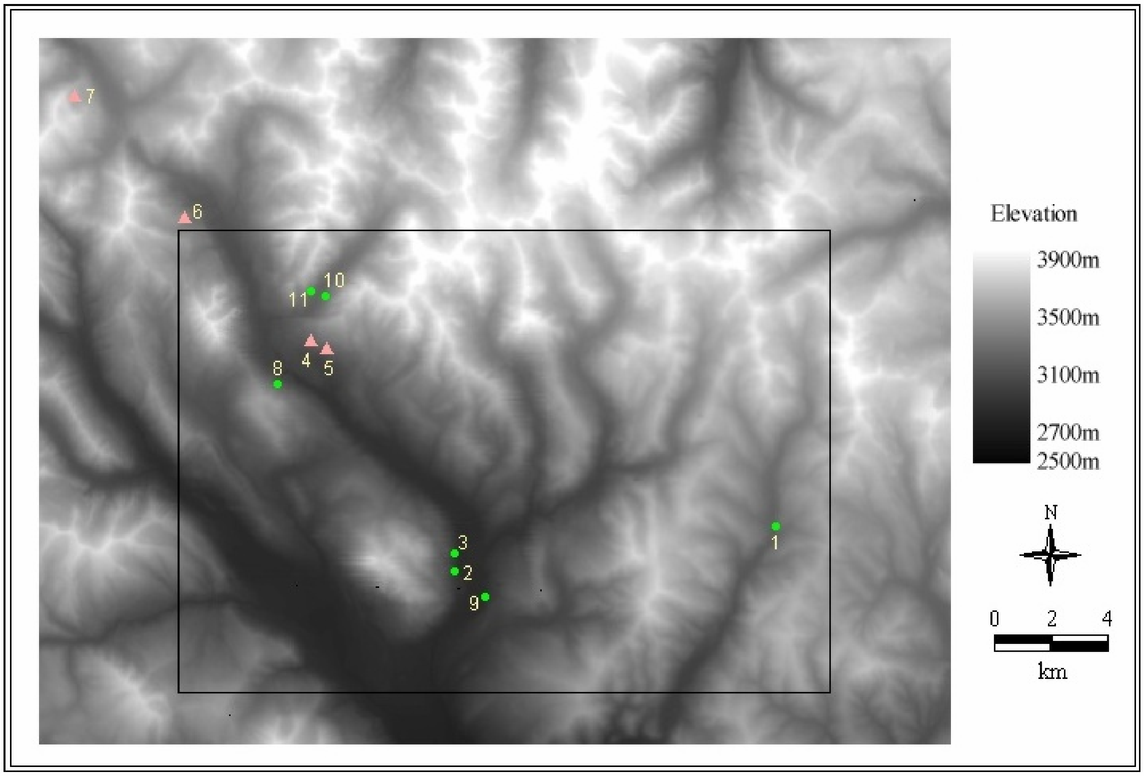


Fig. 1. Locations of soil temperature sensors shown on the DEM for the immediate vicinity of RMBL. Circles indicate sensors used in this analysis (n=7) and triangles indicate sensors that did not collect usable data during the first year of study (n=4).

**Field Measurements of Temperature:** In August of 1998, we buried eleven Hobo soil temperature sensors at 20 cm depth (Onset Computer Corporation, Bourne, Massachusetts) for a series of locations with different aspects, slopes, and upward-looking viewsheds. Exact locations of the sensors were surveyed using a differential corrected global positioning system (Trimble Pathfinder) (Fig. 1). Temperature was logged hourly. Time of hourly readings was converted to local solar time for analyses. In June 1999, the sensors were dug up and sensor readings were downloaded. Of the eleven sensors, three were dug up by animals, and one had a bad connection. In July and August of 1999, these eleven sensors and another ten new sensors were buried again (n=21 total) to collect more data for future analysis. The analysis presented here uses measurements for the seven functioning sensors between10 August 1998 to 17 June 1999. For most statistical analysis, seven samples would be an insufficient sample size. however the data are highly resolved temporally and for key positions in the landscape. Further, weather stations are much more sparsely distributed, and most do not record soil temperature. Many landscape scale studies (covering several hundred square kilometers) have even fewer soil temperature measurements available. Our analyses explore the practical limitations of extrapolation from a small set of sampling stations.

**Interpolation/Extrapolation of Temperature Surfaces:** The Solar Analyst was used to calculate insolation for average clear sky conditions for the field study area. A 30-m DEM surrounding the field area was used as input. Insolation was calculated for one month (10-Aug-98 to 9-Sept-98) and then divided by 31 days to determine average daily insolation. Correlations of insolation with maximum, minimum, daily range (maximum minus minimum) were examined and regressions were used to generate soil temperature surfaces over the entire field study area. Residuals were analyzed against other factors.

## 2.3 RESULTS AND DISCUSSION

**Differences in Diurnal Patterns of Temperature According to Landscape Position:** During most of the period for which temperature measurements were available, the seven sampling locations had very different temperature regimes. Only during November, when snow started accumulating, and during late March and early April, when snow started melting, did most locations have similar temperatures, all fluctuating near $0^o$ C. During the winter, temperatures of sensors at different locations ranged from $–0.2^o$ C to $–7.5^o$ C. This variation was related to differences of snow accumulation and snow depth, with the lowest temperatures associated with less snow cover. Both late summer (August to September) and late spring (May to June) showed high variation between sensors (Fig. 2). Average daily pattern for late summer shows that the daily minimum temperatures were quite similar ($2^o$ C range) and the daily maximum temperatures were very different ($10^o$ C range).

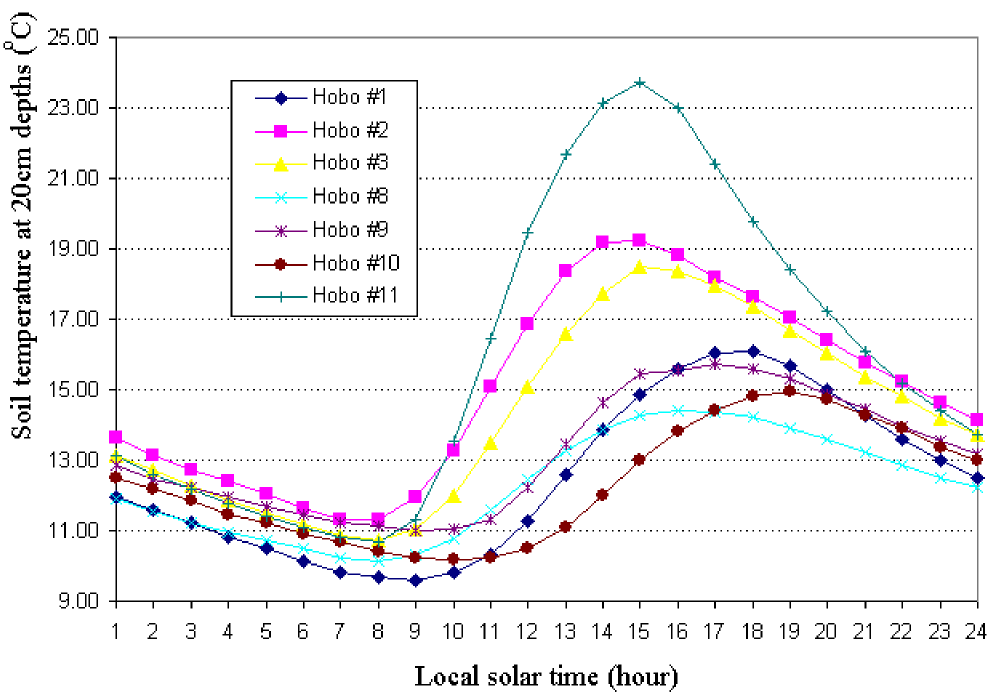


Fig. 2. Diurnal patterns of soil temperature for different spatial location during late summer (10-Aug-98 to 9-Sep-98, measurements averaged for each time hourly interval).

**Correlations of Temperature with Elevation and Insolation:** While daily minimum temperature is strongly negatively correlated with elevation (r = –0.730), it is not correlated with insolation (r = –0.005).

This can be explained by adiabatic lapse rate, which causes predictably lower the temperature with increasing elevation. While daily maximum temperature has a strong positive correlation with insolation (r=0.479), it has no significant correlation with elevation (r=0.034). Insolation is more strongly correlated with daily temperature range (r=0.504) than with maximum temperature. Heating during the day depends in large part upon differences of insolation to different sites.

Table 1. Correlation coefficients of temperature with elevation and insolation (10-Aug-98 to 9-Sept-98).

| | Max | Min | Average | Max – Min |
|---|---|---|---|---|
| Elevation | 0.041 | –0.730 | –0.21 | 0.183 |
| Insolation | 0.479 | 0.034 | 0.367 | 0.504 |

Based on these relationships, linear regressions were calculated between daily minimum temperature and elevation (equation 1), and between daily temperature range and daily insolation (equation 2). These equations were applied to the field study area and maps of daily minimum and maximum temperature were generated (Fig. 3). The map predicts higher soil temperatures for lower elevation and south-facing slopes with high exposure, lower temperatures for north-facing slopes and other slopes with low exposure.

$$\text{Temperature}_{min} = -0.0025 * [\text{elevation}] + 17.90 \qquad (1)$$

$$\text{Temperature}_{max} - \text{Temperature}_{min} = 0.003629 * [\text{insolation}] - 15.01 \qquad (2)$$

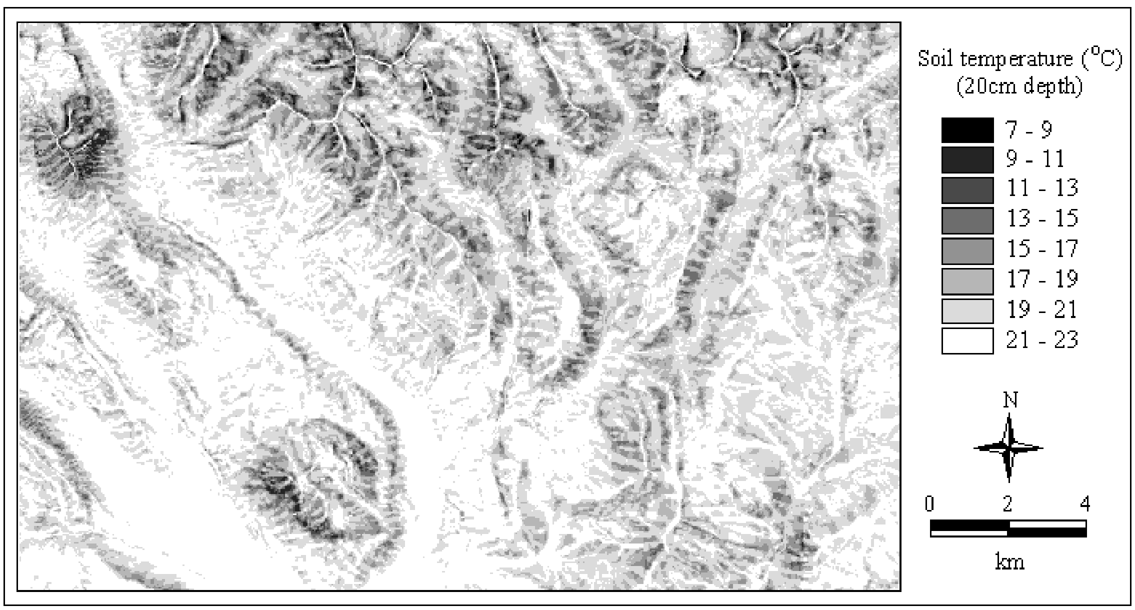


Fig. 3. Map of average daily maximum temperature for late summer (10-Aug-98 to 9-Sep-98).

**Residuals of Regressions:** The resultant maps capture the complex spatial patterns of soil temperature at a fine resolution. Insolation was key to the model, and relates directly to a physical understanding of the system. The root mean square errors (RMSEs) are 0.98$^{o}$ C and 6.46$^{o}$C for equations 1 and 2 respectively. The residual variation can be explained by various factors, including sensor placement, vegetation cover, and DEM quality. Other factors, such as differences in air flow patterns, soil properties, and water content are not considered here.

- **Sensor Placement**: The distances from sensors to ground surface varies with slopes (Fig. 4). The

Larger the slope, the closer the direct line distance to the surface. This effect must be considered when examining soil conductivity. A simple linear correction increases the correlation coefficients between insolation and daily temperature range from 0.504 to 0.688.

- **Vegetation Cover**: Crude categories of vegetation cover were recorded for each sensor location (bare, low, medium, high). Locations with positive residuals have low or no vegetation cover, while locations with negative residuals have high vegetation cover. More detailed analyses must include consideration of differences in vegetation cover.

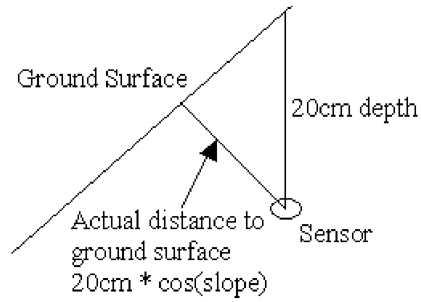


Fig. 4 Actual distance between sensor and ground surface on a slope.

- **DEM quality**: High spatial resolution and high quality DEMs are needed for high-resolution temperature. In this analysis we used the USGS 30 m DEM, which is known to have many problems. This could result in errors in slope, aspect, and the derived viewshed, all of which can affect insolation calculations. We noted differences between the DEM–derived and field measured slopes and aspects at the sensor locations. Using field measured slope and aspect improved the correlations between insolation and soil temperature by approximately 0.06.

## 3.0 OTHER APPLICATIONS

The example of using insolation in temperature surface calculation, is just one of many potential applications. Because solar radiation is the primary input for energy balance, and also the driving force for water balance, insolation is important for all of the physical and biological processes in agriculture and forestry. For example, soil moisture and air relative humidity are negatively related with insolation, potential transpiration and evaporation are positively related with insolation. Insolation submodels would ideally be incorporated in models of forest and crop growth, productivity, crop zone planning, local–scale soil moisture and irrigation, non–point source pollution, forest fire risk assessment, wildlife habitat, and biotic changes under different climate scenarios. In addition, the Solar Analyst can be applied in remote sensing for radiometric normalization of topographic influences; incorporation of a spectral model will improve performance for this purpose.

## 4.0 CONCLUSION

The Solar Analyst provides a powerful set of insolation modeling tools that can be used for diverse applications in agriculture and forestry. Because insolation is expensive to measure directly and difficult to model, many researchers have not included rigorous insolation components in their applications. In our application of the Solar Analyst to produce soil temperature surfaces, insolation proves to be a critical factor because of our need to understand fine-scale patterns. Similarly, any application that involves energy or water balance, either directly or indirectly, could benefit from such detailed insolation analyses. In a world of growing population and limited resources, better understanding of insolation patterns can enable more efficient use of resources and more responsible land planning.

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