24

Dubayah, R. and P.M. Rich. 1996. GIS-based solar radiation modeling. pp 129-134. In: MJ. Goodchild, L.T. Steyaert, B.O. Parks. C. Johnston, D. Maidment, M. Crane, and S. Glendinning (eds). GIS and environmental modeling: progress and research issues. GIS World Books. Fort Collins, Co.

GIS-Based Solar Radiation Modeling

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Incident solar radiation at the earth's surface is the result of a complex interaction of energy between the atmosphere and the surface. Recently much progress has been made toward the creation of accurate, physically based solar radiation formulations that can model this interaction over topographic and other surfaces (such as plant canopies) for a large range of spatial and temporal scales. The ability to implement such models has been facilitated by the development of powerful analysis tools that are part of some GIS environments. In this chapter, we summarize our current work on solar radiation models and their implementation within both GIS and image processing systems. Within this context we focus on several issues including the selection of appropriate physical models, modeling languages, data structures, and model interfaces. An overview of the effects of topography and plant canopies is presented along with a discussion of various options for obtaining the data necessary to drive specific solar radiation formulations. Examples are given from our own work using two models: (1) ATM, a model based within an image processing framework, and (2) SOLARFLUX, a GIS-based model. We consider issues of design including GIS implementation and interface, computational problems, and error propagation.

INTRODUCTION

Topography is a major factor in determining the amount of solar energy incident at a location on the earth's surface. Variability in elevation, slope, slope orientation (aspect), and shadowing, can create strong local gradients in solar radiation that directly and indirectly affect many biophysical processes such as primary production, air and soil heating, and energy and water balances (Geiger 1965; Holland and Steyn 1975; Gates 1980; Kirkpatrick and Nunez 1980; Dubayah 1992). Although it has been recognized that topographic effects are important, until recently little has been done to incorporate them in a quantitative and systematic manner into a modeling environment (Rich and Weiss 1991; Dubayah 1992; Hetrick et al., "GIS," 1993, "Modeling," 1993; Saving et al. 1993). Three factors have limited the progress on topographically based solar radiation models; (1) the complexity of physically based solar radiation formulations for topography; (2) lack of data needed to drive such formulations; and (3) lack of suitable modeling tools.

A GIS, running on a fast, new-generation workstation, can provide the appropriate modeling platform for formulating and running sophisticated solar radiation models (Hetrick et al., "GIS," 1993, "Modeling," 1993). Many of the necessary capabilities are now widely accessible from GIS platforms, including the ability to construct or import digital elevation models (DEM), to integrate diverse databases for input and output, to access viewshed analysis algorithms that permit assessment of sky obstruction and reflectance, and to harness the computational power required for complex calculations.

In this chapter we provide an overview of our research on solar radiation models and their implementation. We first consider topographic effects on direct and diffuse fluxes. We then outline methods for obtaining the data necessary to drive radiation models. Examples of solar radiation modeling using two existing models are presented, one of which (the SOLARFLUX model) is currently implemented within a GIS. We briefly discuss design considerations, data needs, data structures, error propagation, and directions for the future.

MODELING TOPOGRAPHIC AND CANOPY EFFECTS

Detailed descriptions of some topographic solar radiation models can be found in Dozier (1980, 1989), Dubayah et al. (1990), Dubayah (1992), and Hetrick et al. ("GIS," 1993, "Modeling," 1993). Here we briefly summarize the topographic effects most models should consider. There are three sources of illumination on a slope in the solar spectrum: (1) direct irradiance, which includes self-shadowing and shadows cast by nearby terrain; (2) diffuse sky irradiance, where a portion of the overlying hemisphere may be obstructed by nearby terrain; and (3) direct and diffuse irradiance reflected by nearby terrain toward the location of interest.

Direct Irradiance

The direct irradiance is a function of solar zenith angle and the solar flux at the top of the atmosphere (exoatmospheric flux). Zenith angle and exoatmospheric flux vary by date, while transmittance is a function of absorbers and scatterers that can vary greatly over time. Given an optical depth of τ_0, the irradiance is

$$\mu_0 s_0 e^{-\tau 0/\cos\theta 0} = [\cos\theta_0 \cos S + \sin\theta_0 \sin S \cos\varphi_0 - A] S_0 e^{-\tau 0/\cos\theta 0} \quad (24\text{-}1)$$

where S_0 is the exoatmospheric solar flux, θ_0 is the solar zenith angle, φ is the solar azimuth, A is the azimuth of the slope, and S is the slope angle. Both S and A are derived from digital elevation data. For clear sky conditions the spatial variability of incoming solar radiation will usually be dominated by (24-1). However, shadowing must also be taken into account.

Diffuse Irradiance

Unlike direct irradiance, exact calculation of the diffuse irradiance on a slope is difficult and almost always involves some degree of approximation. In addition to changing elevation, two factors must be considered: (1) anisotropy in the diffuse irradiance, and (2) the amount of sky visible at a point (its sky view factor).

Anisotropy: In general, diffuse irradiance is not isotropic, that is, it varies depending on sky direction. Experience tells us that for clear sky conditions this is the case, given the familiar observation of a brighter sky near the horizon and near the disk of the sun. However, modeling anisotropy can be complex, especially under partly cloudy conditions. This is further complicated because atmospheric conditions can change rapidly. To simplify the problem we often assume that the diffuse radiation coming from the sky is isotropic.

Sky view factor: At any given location, a portion of the sky may be obstructed by topography, thereby reducing diffuse irradiance from corresponding sky directions, Sky obstruction can result either from "self- shadowing" by the slope itself or from adjacent terrain. A sky view factor V_d can be calculated that gives the ratio of diffuse sky irradiance at a point to that on an unobstructed horizontal surface. In theory the diffuse flux should be calculated by multiplying the view factor in a particular direction by the amount of diffuse irradiance in that sector of the sky, and integrating over the hemisphere of sky directions. This is computationally complex and storage intensive because it requires the calculation of V_d and diffuse irradiance for each sky sector and for each grid point. If we assume that diffuse irradiance is isotropic, only one view factor is associated with each grid location (as opposed to a factor for each direction). Using an isotropic assumption, the diffuse irradiance is given by

$$V_d = F{\downarrow}\tau_0 \qquad (24\text{-}2)$$

where $F{\downarrow}\tau_0$ is the average diffuse irradiance on a level surface at that elevation, and V_d varies from 1 (unobstructed) to 0 (completely obstructed). Dozier and Frew (1990) provide details on finding V_d using horizon angles. Hetrick et al. ("GIS," 1993) give a highly simplified formulation for diffuse flux on a slope based on Gates (1980).

Some GIS environments provide a viewshed capability that delineates for a given point the area that can be seen from that point. The points that make up the border of the viewshed form the horizon for that point. Using this viewshed approach (Hetrick et al., "Modeling," 1993, Rich et al., in press), view factors can be calculated.

Reflected Irradiance

For each point, reflected radiation from surrounding terrain must be estimated. One method of doing this is by calculating an average reflected radiation term and adjusting this by a terrain configuration factor. This configuration factor, C_t, should include both the anisotropy of the radiation and the geometric effects between a particular location and each of the other terrain locations that are mutually visible. The contribution of each of these terrain elements to the configuration factor could be computed, but this is difficult. We can again simplify by assuming (unrealistically) that the radiation reflected off of terrain is isotropic and given that V_d for an infinitely long slope is (1+cosS)/2, approximate C_t by

$$C_t = \frac{1 + \cos S}{2} - V_d \qquad (24\text{-}3)$$

The reflected radiation from the surrounding terrain is then

$$C_t\, F{\uparrow}(\tau_0) = C_t\, R_0\, F{\downarrow}\tau_0 \qquad (24\text{-}4)$$

where $F{\uparrow}(\tau_0)$ is the amount of radiation reflected off the surface with an average reflectance of R_0. Hetrick et al. ("GIS," 1993) implement a formulation of Gates (1980) for this as well. As with the sky view factors, there is the possibility that viewshed programs could be exploited to improve the estimate of reflected radiation.

Total Irradiance on a Slope

Given the assumptions above, one physical formulation for the total irradiance on a slope (see Hetrick et al., "GIS" 1993 for another) can now be given as

$$R{\downarrow}\,(\text{slope}) = [V_d\, F{\downarrow}(\tau_0) + C_t\, F{\uparrow}(\tau_0) + \mu_s\, S_0 e^{-\tau 0/\cos\theta 0}] \qquad (24\text{-}5)$$

where, V_d, C_t, and μ_s are all derived from digital elevation data and all vary spatially. Since τ_0 is a function of pressure, the diffuse radiation will vary spatially with elevation, as will the direct irradiance. Equation (24-5) is implicitly a function of wavelength (i.e., monochromatic). Total irradiance can be found by integrating it with respect to wavelength over the desired spectral interval. A good approximation is to divide the solar spectrum into two broad bands, one mainly scattering and one mainly absorbing, corresponding to the visible and near-infrared, and use (24-5) in each wavelength region.

Canopy Effects and Other Complex Sky Obstruction

Very near the ground, sky obstruction results from local features, in particular plant canopies, nearby terrain, or human-made structures, all of which can present a complex pattern of sky obstruction. Modeling incident solar radiation under circumstances of complex sky obstruction is essentially the same as that already described for locations on a topographic surface. Direct and diffuse components are calculated as the irradiance originating from unobstructed sky directions, integrated over the hemisphere of sky directions (Rich 1989. 1990). However, many problems remain, both in terms of modeling and measurement. Models must account for high temporal variability of sky conditions, anisotropic irradiance distributions, the geometric complexity of plant canopies, and the resulting complex patterns of reflectance (scattering) off of the many canopy surfaces. A comprehensive analysis of sky obstruction would ideally involve detailed three-dimensional reconstruction of canopy architecture combined with viewshed analyses that account for both unobstructed irradiance through canopy openings and scattering. As for terrain models, reflected or scattered components are difficult to measure and model and are commonly ignored because of their relatively small contribution to total irradiance. Rich et al. (1993) suggest that it may be practical to derive digital elevation models of the topographic surface of plant canopies that can be used to provide a first-order estimate of near-ground radiation flux and as input to more complete canopy radiance models.

MODEL DRIVERS

Terrain and Surface Reflectance Data

Terrain data: Topographic radiation models require data about the specific terrain of interest. Specifically, digital elevation and surface reflectance data are needed. Digital elevation data exist for many parts of the world at a variety of grid spacings (Wolf and Wingham 1992). The modeling purpose should determine the grid spacing of the data used (when that option is available). It should be noted that the digital elevation data may not represent terrain, but rather any arbitrary surface, such as buildings and trees. No aspect of the modeling process described here is constrained only to topography. Methodology for quantifying complex sky obstruction using hemispherical photography is well developed (Rich 1989, 1990), however the technique is limited to locations for which high contrast hemispherical photographs can be obtained. The hemispherical photographs are used as a direct measure of sky directions that are obscured and can be taken in transects or arrays that permit examination of spatial patterns (Galo et al. 1992; Lin et al. 1992; Rich et al. 1993).

Surface reflectance data: Information about the reflectance of the surface is required to compute multiple scattering between the surface and the atmosphere (if using radiative transfer to obtain the diffuse flux), the amount of radiation reflected off of nearby terrain for incoming radiation, and the net solar radiation. The multiple scattering component is usually small for most surfaces other than snow and ice. For simulation purposes, a guess at the average area albedo in the visible and near-infrared is usually sufficient.

Radiation Data

For each location, a radiation formulation such as (24-5) requires an estimate of the direct and diffuse irradiance for a level surface at the corresponding elevation. Obtaining these values can be difficult, especially for the diffuse flux. The source and type of radiative drivers used is perhaps the most important implementation issue because it determines whether the model will produce actual solar radiation fluxes for a given time and location or some type of "potential" radiation. For obtaining actual fluxes, some field-measured data must be available, such as pyranometer data, atmospheric optical data, or atmospheric profile (sounding) data. For potential solar radiation, the state of the atmosphere need not be known and some average or reference conditions are assumed.

Radiative transfer algorithms that describe the flux of energy through the atmosphere can be used to get the direct and diffuse fluxes. One common approximation to the radiative transfer problem is the two-stream method (Meador and Weaver 1980). If we have no information about the atmosphere, other radiative transfer programs, such as LOWTRAN7 (Kneizys et al. 1988), can be used to obtain standard atmospheric optical conditions at particular locations for particular times of year. If radiosonde data are available (providing information on the vertical profiles of temperature, water vapor, and pressure, among others) these data can be used in LOWTRAN7 to get more accurate fluxes.

Where pyranometer data are available, empirical formulations can be used to obtain the diffuse irradiance from global irradiance (Dubayah and van Katwijk 1992). Alternately, the pyranometer data may be used to obtain the optical properties needed to run the two-stream model via inversion, though the inversion is not unique (Dubayah 1991). Semiempirical formulations can be used that combine known optical depths with empirically derived equations for the diffuse flux (e.g., see Gates 1980; Hetrick et al. "GIS," 1993, "Modeling," 1993). For purposes of comparing different locations across a landscape, it is often useful to calculate potential solar radiation under a common set of conditions, for example under clear-sky conditions (Hetrick et al., GIS," 1993, "Modeling," 1993; Saving at al. 1993).

EXAMPLES: THE ATM AND SOLARFLUX MODELS

In this section we present some examples from our own research using two different models: (1) ATM (Atmospheric and Topographic Model) (Dubayah 1992), which is derived essentially from Dozier (1980, 1989); and (2) SOLARFLUX (Hetrick et al., "GIS," 1993, "Modeling," 1993). ATM is a collection of separate programs, each of which are part of the Image Processing Workbench (IPW) (Frew 1990), which, although raster based, is not explicitly implemented within a GIS. SOLARFLUX has been used effectively in planning, conservation, microclimate, and basic ecology studies (Rich et al. 1992, 1993; Saving et al. 1993; Weiss et al. 1993). Because SOLARFLUX is implemented in the ARC/INFO and GRID GIS platform (Environmental Systems Research Institute) as an ARC Macro Language program (AML), it provides access to a broad range of GIS capabilities.

ATM

One of the main objectives in the development of ATM was to provide inputs for hydrological and snowmelt models in mountainous terrain. Using existing data, ATM can generate detailed topoclimatologies for large river basins. A good example of this is our modeling efforts in the Rio Grande River basin of Colorado (Dubayah and van Katwijk 1992). A mosaic of thirty-nine DEMs at 30-m grid spacing was created covering the upper portion of the basin, above Del Norte and west to the continental divide. A four-year time series of hourly pyranometer measurements of direct and diffuse fluxes was available for four hydrologic years beginning in 1987. The pyranometer data was used with Landsat Thematic Mapper satellite estimates of reflectance and NOAA estimates of snow-covered area to create a four-year monthly climatology of incoming radiation for the entire basin. Figure 24-1 shows a map of net solar radiation for the month of June 1990 for the entire basin. The highest regions at the western end of the basin are still snow covered and hence have low net radiation values because of high surface reflectance. Note that the reflectance features of the surface are barely visible; rather, it is topography that dominates the spatial variability.

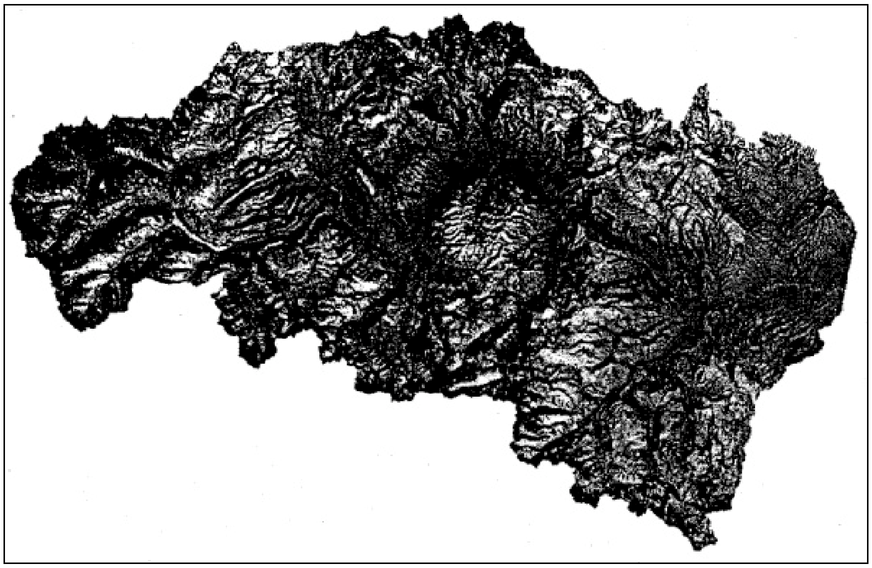

Figure 24.1. Map of net solar radiation for June 1990 for the Rio Grande. Range of values on map is from 35 W/m^2 – 362 W/m^2. The basin is approximately 110-km long.

SOLARFLUX

SOLARFLUX uses input of a topographic surface, specified as a GRID of elevation values, as well as latitude, time interval for calculation, and atmospheric conditions (transmissivity), and provides output of direct radiation flux, duration of direct radiation, sky view factor, hemispherical projections of horizon angles, and diffuse radiation flux for each surface location. Applications of SOLARFLUX have spanned very different temporal and spatial scales. At the landscape level, SOLARFLUX is being used to drive landscape level microclimate-based habitat models for topographically diverse regions (Hetrick et al., “GIS,” 1993, “Modeling,” 1993; Saving et al. 1993). Potential clear sky solar radiation flux can readily be calculated for any day of the year, for example the winter solstice at the Big Creek reserve in California (Figure 24-2a). A shading index, calculated as the proportional reduction in solar radiation due to topographic shading, permits assessment of the importance of topographic shading for each landscape position (Figure 24-2b). At the scale of individual trees in arid woodlands (Rich et al. 1993), SOLARFLUX has been used to examine microclimate heterogeneity as it affects sites where young trees can become established (Figure 24-3).

DESIGN CONSIDERATIONS

Implementation Issues

Implementation within a GIS: Because of the broad range of applications of solar radiation models, GIS developers should be encouraged to integrate basic solar radiation modeling capabilities as part of their software. Though running SOLARFLUX as an AML has the considerable advantage that it can be customized for a particular application, its performance suffers because many of the routines called from the ARC interpreter take much time to load and run. This can easily be remedied by optimizing and compiling the calculation- intensive steps, such as viewshed analysis, while preserving as much flexibility as possible; for example, permitting the user to specify how many sky sectors are examined. The design challenge is to provide the fundamental set of cools to simulate direct, diffuse, and reflected components of solar radiation without sacrificing the ability to customize the inputs, outputs, and precision of calculation.

Interface with outside programs: A GIS-based radiation model should have the ability to easily interface with existing radiative transfer programs such as LOWTRAN7 for input, and with system models, such as energy or water-balance simulation for output. For example, the ATM model allows the user to specify the same model atmospheres included in LOWTRAN7. It then finds the range of elevations in the DEM, runs LOWTRAN7, and produces a lookup table of diffuse and direct fluxes over the range of elevations. The ability of ATM to interface with these programs is critically linked to its overall design structure. Specifically, the decoupling of elevation from other topographic effects allows for a midstream modeling interaction with radiative transfer programs.

Computational problems: The major computational problems concern the calculation of the sky view and terrain configuration factors and

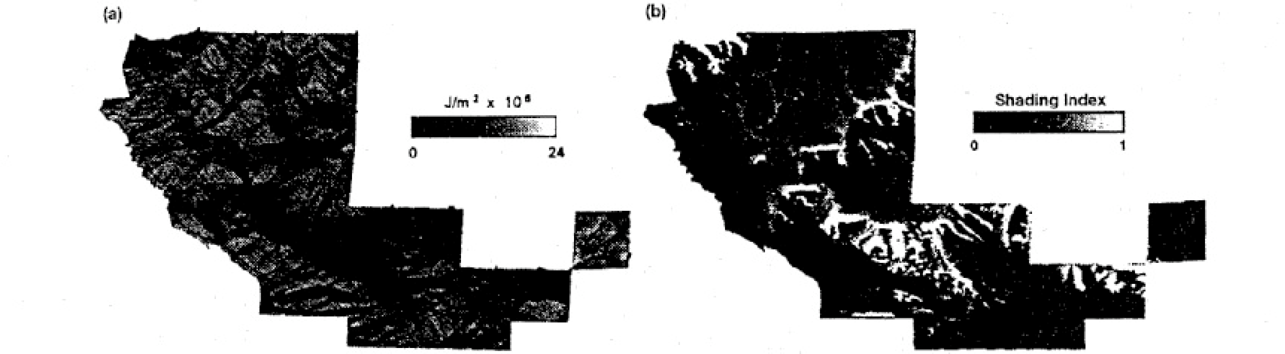

Figure 24-2. (a) Daily direct insolation on the winter solstice for Big Creek reserve (Hetrick et al., “GIS”, 1993). (b) Shading index, expressed as proportional decrease in direct insolation due to topographic shading (Hetrick et al., “GIS”, 1993).

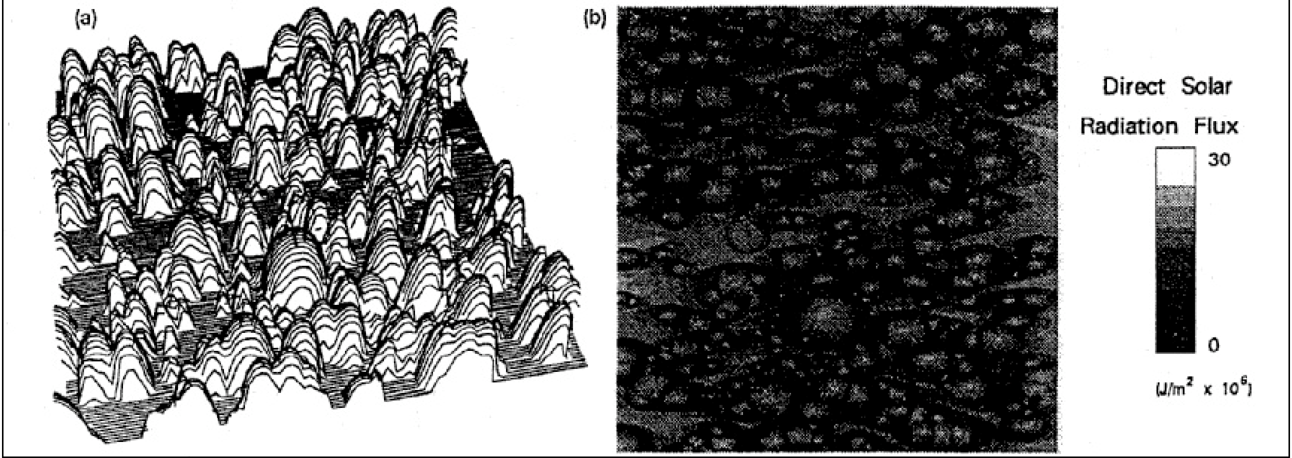

Figure 24-3. (a) The canopy surface topography of a 1-ha plot in pinyon-juniper woodland at the Los Alamos National Environmental Research Park, New Mexico. Surface topography was reconstructed based on maps of individual trees and assuming that crown form could be approximated as the upper half of an ellipsoid, with the height as the major axis and the crown as the minor axis. (b) Simulated daily solar radiation flex on the summer solstice (Rich et. al)

canopy interactions, although this is not an issue if simple approximations to these are used. If these factors are preprocessed, the majority of the computation is then involved in determining shadowing and terrain reflected flux. If anisotropy is considered, the calculation of reflected flux could be prohibitive. Further research is needed on creating a computationally efficient means for handling anisotropy, especially with an intervening canopy. An approach that uses highly optimized lookup table approaches, such as those employed by Rich (1989) for analysis of hemispherical photographs and incorporated in SOLARFLUX (Rich et al., in press), may be the key to efficient calculations that incorporate anisotropy.

Error Propagation

There are errors associated with every step of solar radiation modeling: (1) associated with the radiative transfer calculations (e.g., the two-stream approximation is no better than 10% - 15%); (2) associated with interpolating and extrapolating empirical measurements over a landscape; (3) associated with registration (between reflectance and digital elevation data); and (4) associated with approximations particular to a physical model. The most serious source of error, however, is the poor quality of most digital elevation data. For example, the USGS 30-rn DEMs have considerable noise that often produces inaccurate slopes and aspects for any given location. Therefore, not only is the gradient in error, but also view factors and terrain configuration factors. This in turn affects both the direct and diffuse irradiance calculations. If the radiation maps are then used to drive hydrologic or energy balance models, the errors that originate with the DEM are carried very far indeed from their source. For other digital elevation data, such as created from low-flying aircraft, or in the case of plant canopies, reconstructed from hemispherical photographs, the same cautions apply.

FUTURE DIRECTIONS

Given the complex interactions that take place between the atmosphere, topography, and plant canopies, solar radiation models can become highly elaborate. Obtaining increasingly better estimates of actual solar radiation should not be the only goal as the models evolve. The ability to calculate either potential or some type of simulated radiation must be retained. This is especially true in the areas of ecological modeling and global climate-change modeling. As models become more complex they can become more difficult to use, mainly because of the requirement of additional input data. Thus it is important that future models avoid this pitfall by allowing for flexibility with regard to the type of radiation calculated and the input data needed.

There are a variety of extensions that we anticipate in the near future. These include adding anisotropy to the diffuse and reflected terrain calculations and incorporating further canopy effects (see Rich, in press). One important factor, not covered so far, is clouds. Some capability for modeling scattered clouds should be incorporated (see Dubayah et al. 1993). At a local scale, incorporation of ongoing solar radiation measurements can be used to assess either short- or long-term importance of clouds (Rich et al. 1993). Another difficult problem is modeling true three-dimensional surfaces, where there may be more than one height coordinate associated with a given spatial location (as in the case of overlapping plant canopies). Most GIS cannot readily handle true three-dimensional surfaces. Work is needed on the representation of such surfaces and the computation of energy transfer through them.

CONCLUSION

Whether used for hydrologic or ecological modeling, for agriculture or forestry; for conservation or management, or for engineering and design, there is no shortage of applications that require the ability to model solar radiation intercepted by complex topographic surfaces. Much of the theory is now in place, and implementation is progressing rapidly. GIS provide the ideal modeling environment for interface of inputs and outputs of solar radiation models. Models such as SOLARFLUX and ATM serve as prototypes for a future generation of solar radiation models that should be an integral part of any GIS toolbox.

Acknowledgments

This work was supported by NASA grants #NAGW-2928 and #NAG 5-2358; the University of Maryland Laboratory for Global Remote Sensing Studies; the University of Kansas Research Development Fund; the Los Alamos National Laboratory Environmental Research Park; the Kansas Applied Remote Sensing Program; and the Kansas Biological Survey. Additional support was provided by Calcomp, Inc.; Environmental Systems Research Institute, Inc.; and SUN Microsystems, Inc. We thank William Hetrick, Sara Loechel, Shawn Saving, and Stuart Weiss for their various input.

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