USING VIEWSHED MODELS TO CALCULATE INTERCEPTED SOLAR RADIATION: APPLICATIONS IN ECOLOGY

by

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Citation:

Rich, P.M., R. Dubayah, W.A. Hetrick, and S.C. Saving. 1994. Using viewshed models to calculate intercepted solar radiation: applications in ecology. American Society for Photogrammetry and Remote Sensing Technical Papers. pp 524–529.

ABSTRACT

The solar radiation intercepted at a given location on the earth's surface is influenced by surface orientation and sky obstruction by surrounding topographic features. Viewshed models can be used to calculate sky obstruction for any given location on or above a complex topographic surface. We have developed an algorithm for rapid calculation of intercepted solar radiation using a combination of viewshed analysis and a lookup table of irradiance from each sky direction. First, the angular distribution of sky obstruction is calculated for the location of interest and stored in a hemispherical coordinate system. Then lookup table values for all unobstructed sky directions are summed to determine total irradiance. Angle of incidence is accounted for using a cosine correction. The process can be repeated across a topographic surface to determine the /Spatial distribution of intercepted solar radiation. The results can be expressed as energy flux or as sky view factors. This lookup table approach accounts for anisotropic irradiance distributions and can treat different spectral bands separately. The same viewshed approach can be used for optimizing calculation of reflected radiation from topographic surfaces. This approach will be especially valuable for studies of ecological processes, by permitting assessment of topographic influences on energy balance and microclimate.

INTRODUCTION

While the processes that determine the solar radiation reaching the earth's surface are reasonably well understood (Gates 1980, Lunde 1980), modeling these proccsses presents considerable challenges. Recent advances in computer software and hardware provide us with the tools necessary to perform the large numbers of calculations required for detailed models that can examine temporal and /Spatial variability of incident solar radiation at a landscape level. Work on topographically based models has focused on simulating the solar radiation incident on or above a specified topographic surface (Dubayah 1992, Dubayah and Rich in press, Hetrick et al. 1993a, 1993b), with applications at local (Galo et al. 1992, Rich et al. 1993a) and landscape scales (Saving et al. 1993). These models account for effects of surface orientation and sky obstruction by topographic features. New, efficient algorithms are needed that enable formulation of more realistic models, for example accounting for anisotropy of irradiance.

Scope of This Paper: Herein we describe a flexible and efficient algorithm for rapid calculation of intercepted radiation based on viewshed analysis of sky obstruction and lookup tables of irradiance as a function of sky direction. The viewshed analysis involves geometric calculation of the set of directions that are visible from a given location, in particular evaluation of which sky directions are obscured. The lookup table approach involves storage of a set of irradiance values, either derived theoretically or empirically using sensors, that correspond to each of a set of predefined sky sectors. This algorithm was originally developed for use in analyzing hemispherical photography (Rich 1989, Rich 1990), but can be more generally utilized to evaluate complex patterns of sky obstruction and to account for anisotropic distributions of incoming solar radiation.

AN ALGORITHM FOR CALCULATION OF INCIDENT SOLAR RADIATION

Our Approach to Solar Radiator Modeling: For each location of interest, solar radiation models must account for direct and diffuse radiation originating from the overlying hemisphere of sky directions, as well as radiation reflected from surrounding surfaces. If we assume that the contribution of reflected radiation is negligible, incident solar radiation can be calculated as the sum of direct and diffuse irradiance from all sky directions, calculated over any time interval of interest. This calculation can be accomplished in a two step process. First, the angular distribution of sky obstruction can be evaluated. Second, the total irradiance can be calculated by summing irradiance values for all sky directions that are not obscured. This second step must also account for the angle of incidence, with an appropriate cosine correction relative to the interception surface. This process can be performed iteratively for all locations in a landscape to map the /Spatial variation of incident solar radiation.

The General Algorithm: The algorithm developed by Rich (1989, 1990) for analysis of hemispherical photography can be generalized in the following way. First, the angular distribution of sky obstruction is specified in a hemispherical coordinate system, in which the hemisphere of sky directions is projected on a plane (Figure 1). Second, the sky is divided into a discrete number of sectors, corresponding to reasonably small ranges of zenith and azimuth angles, and the angular area of unobstructed sky corresponding to each sky sector is determined (Figure 2). Third, for each sky sector the proportion of unobstructed sky is multiplied by the corresponding irradiance for that entire sky sector, and by a factor that provides a cosine weighting appropriate for the angle of incidence of between the sky sector and the surface of interest. Finally, the resulting radiance values of all sky sectors, which now account for sky obstruction and angle of incidence, are summed to obtain total incident radiation for the location of interest.

Evaluation of Sky Obstruction: Sky obstruction can be evaluated either empirically using hemispherical photographs taken for each location of interest or else calculated based on geometry. In the latter case, the surface topography must be known (for instance as a digital elevation model) and viewshed analysis can be used to calculate sky obstruction. This viewshed analysis involves searching in a set of specified directions around the location of interest and calculating the maximum angle of sky obstruction, also referred to as horizon angle, in each direction (Dozier and Frew 1990). In essence, this permits calculation of a hemispherical viewshed of sky obstruction.

Sky Sector, Irradiance, and Cosine Weighting Lookup Tables: Division of the hemisphere of sky directions into sky sectors is accomplished using a large lookup table, in which each location in the hemispherical projection is assigned a value that corresponds to the appropriate sky sector. Similarly, lookup tables are employed to specify the irradiance corresponding to each sky sector and to specify the appropriate cosine weighting factor. It is commonly useful to break the analysis into separate treatments for direct and diffuse components of radiation. For direct radiation, which originates directly from sun, it is useful to define sky sectors according to the time of day and year, for example by half-hour intervals through the day and month intervals through the year (Figure 2a). For diffuse radiation, which can originate from any sky direction, it is useful to divide the sky symmetrically into relatively

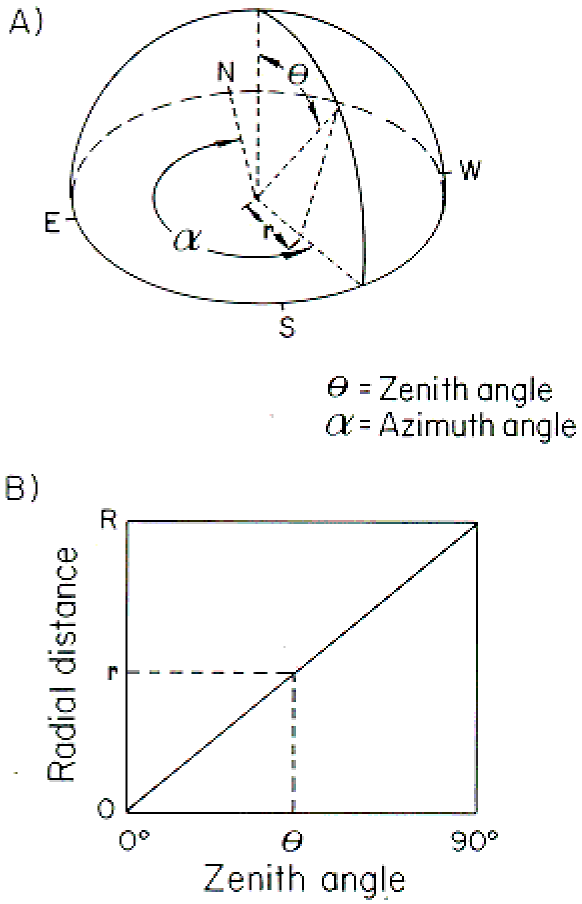

Figure 1. In a hemispherical coordinate system, the hemisphere of sky directions is projected on a plane, resulting in a circular map in which the zenith is in the center, the horizons at the periphery, east to the left, and west to the right. B) In an equiangular hemispherical projection, distance along a radius (r) is proportional to zenith angle. (after Rich 1989)

highly resolved ranges of zenith and azimuth angles (Figure 2b).

The division of sky directions into discrete sectors must be performed at a fine enough scale to minimize calculating errors that result from three distinct problems. First, it is generally necessary to calculate unobstructed sky as a proportion of area in a hemispherical coordinate system for which angular area is not necessarily preserved. Second, there may be anisotropy of irradiance from different directions within a sky sector. Third, the cosine weighting is generally calculated relative to the centroid of a sky sector and therefore has an error associated with it that depends upon the angular area and shape of the sector.

Irradiance values can either be expressed in actual units or as a proportion of the total value from a fully unobscured sky. Similarly, irradiance values can correspond to any given wavelength or set of wavelengths. Irradiance values can be integrated over any time interval of interest (e.g., instantaneous, day, or year) and may be either derived theoretically or empirically using pyranometers or quantum sensors (Rich et al. 1993b). For purposes of comparison of different topographic locations, it is common to simulate clear sky conditions or "potential" radiation. This latter approach is especially useful for locations where sensor measurements are not available. However detailed sensor measurements and simulation of radiative transfer may be necessary for better estimates of actual radiation flux.

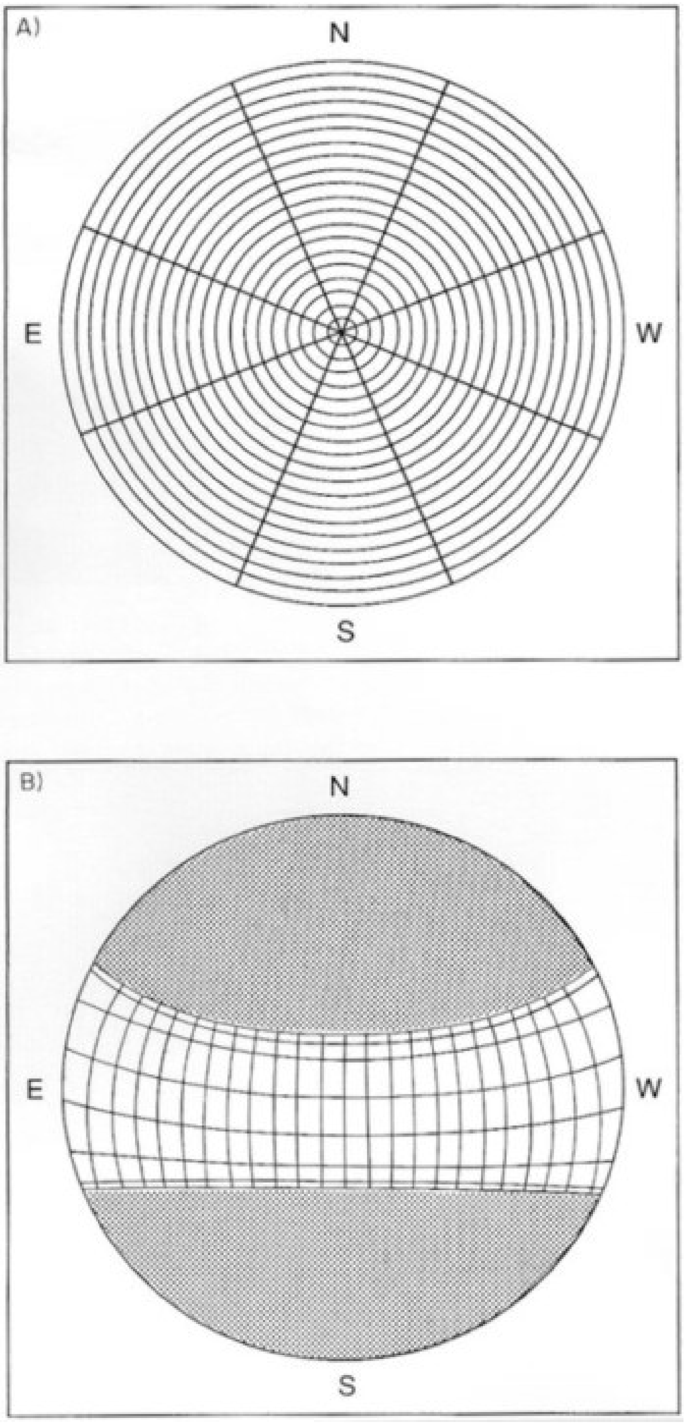

Figure 2. An example of division of the sky into 160 sectors, with 20 equal ranges of zenith angles and 8 ranges of azimuth angles. This classification is appropriate for use when examining diffuse solar radiation from all sky directions. B) An example of division of the sky into 168 sectors, each of which corresponds to a range of apparent sun positions at half-hour intervals through the day and month intervals through the year. This classification is appropriate for examining direct solar radiation, in this case for examining direct solar radiation, in this case for 10.43° north latitude (for use at La Selva Biological Station, Costa Rica). Seven horizontal regions define month periods because the sun sweeps across each region twice during each year (after Rich 1989).

Site Factors and Sky View Factor: For analysis of hemispherical photography, calculations of incident solar radiation are commonly expressed as direct and diffuse site factors, which refer respectively to the proportion of direct and diffuse radiation relative to that received from an obstructed sky (Rich 1989, 1990). Sky view factor, which in some formulations can be equivalent to diffuse site factor, refers to the ratio of diffuse sky irradiance at a given location relative to that on an unobstructed horizontal surface. Commonly, an isotropic distribution of diffuse irradiance as a function of sky direction is assumed, which permits calculation of a single sky view factor for a given location (see Dosier and Frew 1991). To account for anisotropy, a separate sky view factor and irradiance value must be calculated for each sky sector. The algorithm described herein provides an effective means for calculating sky view factors and can accommodate either isotropic or anisotropic irradiance distributions.

Accounting for Reflected Radiation: Until now, we have neglected the contribution of reflected radiation, which can be important, especially in cases involving surfaces with high albedo, such as snow fields. Behavior of reflected radiation is complex because of high variation in reflectance properties, surface orientations, shadow patterns, etc. However, the algorithm described in this paper can be used to permit calculation of simplified estimations or indices of reflected radiation. Using this approach, reflected radiation incident on a given location can be calculated by determining which sky directions are obstructed, assigning reflected irradiance values to each direction in which the sky is obstructed, and summing these irradiance values. For locations above the earth's surface or on slopes, a hemispherical view downward could be used to account for upwelling radiation. In addition, a terrain view factor, similar to a sky view factor, could be defined as a proportion of reflected radiation reaching a given location relative that which could strike a horizontal surface from all obstructed sky directions. Even a simple index of the proportion of obstructed sky may be useful as a first order approximation of reflected radiation values.

Ecological Applications

Topographically based solar radiation models have applications in a broad range of fields that deal with earth system processes, including agriculture, forestry, hydrology, and ecology. Our primary interest in developing the algorithm for calculation of incident solar radiation has been for use in our studies of ecological processes. In particular, we are interested in assessing the influence of topography on microclimate as it determines energy and water balances and as it affects habitat suitability for biological organisms. We are applying topographically based solar radiation models at local scales to examine the influences of individual trees on nearground energy and water balance (Rich et al. 1993a), and at landscape scale to assess habitat quality in natural reserves (Saving et al 1993).

CONCLUSION

Solar radiation is the primary source of energy at the earth's surface, and topography is a primary factor modifying the radiation reaching any particular /Spatial location. Herein, we have presented a general algorithm that permits rapid and effective calculation of topographic influences on intercepted solar radiation based upon knowledge of sky obstruction, irradiance as a function of sky direction, and surface orientation. The viewshed approach permits us to assess sky obstruction for any location on or above a topographic surface, while the lookup table approach allows rapid calculation and accounts for anisotropic distributions of irradiance. Moreover, the algorithm is flexible, in that it permits choice of the level of resolution to use in simulations and accommodates either empirical solar radiation measurements derived from sensors or theoretical irradiance functions based on first principles.

ACKNOWLEDGMENTS

This work was supported by NASA grants NAGW-2928 and NAGS-2358, the University of Kansas Research Development and General Research Funds, the Kansas Biological Survey, the Kansas Applied Remote Sensing Program, and the University of Maryland Laboratory for Global Remote Sensing Studies. We thank Andrew Weiss and Stuart Weiss for critical discussion of our approach, and Diane Debinski and Mark Jakubauskas for editorial comments.

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