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# Incorporating Landscape Heterogeneity in Land Surface Albedo Models

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The importance of incorporating landscape heterogeneity into climate models has been recognized by a number of researchers. However, attempts to relax the assumption of uniform, homogeneous and complete vegetation cover have generally been limited to modeling each component of the landscape (e.g., trees, grasses, shrubs) as a homogeneous unit and then combining the results for each type, weighted by the percentage of ground area it covers (i.e., an area-weighted average is computed).

The purpose of this paper is to demonstrate that substantial errors in the representation of vegetation-atmosphere interactions can arise from the assumption of landscape homogeneity. Even when weighted averages are employed as a first attempt to consider landscape heterogeneity, the underlying assumption of homogeneity of the vegetation patches can lean to significant errors. To demonstrate an example of how this can occur, vegetation canopy albedo derived from weighted averages is compared to that computed with explicit consideration of canopy heterogeneity.

## INTRODUCTION

In the past decade, efforts have been made to incorporate more realistic parameterizations of land surface processes into atmospheric general circulation models (GCMs). Several of these parameterizations have taken the form of vegetation canopy submodels that estimate the radiative, convective and conductive, fluxes between the surface and the atmospheric boundary layer, most notably the Biosphere-Atmosphere Transfer Scheme (BATS) [*Dickinson et al.*, 1981, 1986; *Wilson et al.*, 1987] and the Simple Biosphere model (SiB) [*Sellers et al.*, 1986; *Sato et al.*, 1989]. These models all assume that the vegetation type (e.g., forest, grassland, tundra) remains constant across each GCM grid element. Since these grid elements have a characteristic horizontal dimension of the order of several hundred kilometers, they cover an area of the Earth's surface of well over $10^4$ km$^2$. Furthermore, these models assume that the vegetation cover is homogeneous over the entire grid element. This second assumption is highly unrealistic given the normally patchy nature of landscapes at these scales.

The importance of incorporating landscape heterogeneity (i.e., patchiness) into climate models has been demonstrated in a number of studies [*Avissar and Pielke*, 1989; *Avissar and Verstraete*, 1990; *Pielke and Avissar*, 1990; *Verstraete and Dickinson*, 1986; *Verstraete*, 1989; *Avissar*, 1991]. While these studies have focused on vegetation inhomogeneities at scales smaller than the typical GCM grid cell, much generalization of landscape structure is still incorporated. Attempts to relax the assumption of homogeneous vegetation cover have generally been limited to modeling each component of the landscape (e.g., trees, grasses, shrubs) as a homogeneous unit and then combining the results for each type, weighted by the percentage of ground area it covers (i.e., an area-weighted average is computed).

The purpose of this paper is to demonstrate that substantial errors in the representations of vegetation-atmosphere interactions can arise from the assumption of landscape homogeneity. Even when weighted averages are employed as a first attempt to consider landscape heterogeneity, the underlying assumption of homogeneity of the vegetation patches can lean to significant errors. To demonstrate an example of how this can occur, vegetation canopy albedo derived from weighted averages will be compared to that computed with explicit consideration of canopy heterogeneity.

Surface albedo was chosen for this demonstration because it determines the proportion of incident solar radiation absorbed by the Earth's surface and thus the amount of energy available for heating the ground and lower atmosphere as well as for evaporating water. Moreover, specification of land surface albedos has been shown to have a significant impact on climate simulation [*Charney et al.*, 1977; *Preuss and Geleyn*, 1980; *Potter et al.*, 1981]. Studies of the sensitivity of the climate system indicate that significant changes in surface energy fluxes and temperature can result from albedo changes of a little as two percent [*Henderson-Sellers*, 1992].

## ALBEDO MODELING

Both BATS and SiB use a two-stream approximation [*Coakley and Chylek*, 1975; *Meador and Weaver*, 1980] to model the albedo of a vegetation canopy. *Dickinson* [1983] gives a solution for the albedo of a semi-infinite (i.e., optically dense) canopy composed of randomly distributed and uniformly oriented leaves. *Sellers* [1985] extended the two-stream approximation to sparse canopies by including the reflection of radiation from the soil surface and considering nonuniform leaf orientation distributions. These two-stream models are one-dimensional in nature; the canopy is considered to be horizontally homogeneous and of infinite extent, thereby eliminating edge effects. To apply the results of these models to more realistic, nonhomogeneous vegetation canopies, a weighted average based on the relative proportions of ground covered by individual components is computed. For example, the albedo of a savanna with a 25 percent ground cover of deciduous trees would be obtained by weighting the albedo for deciduous forest by 0.25 and the albedo for grassland by 0.75 and then summing. This method misrepresents the three-dimensional nature of the savanna where individual trees or small groups of trees are scattered over a grassy plain. Weighted averaging implies that all the trees are grouped in a dense, homogeneous forest covering 25



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percent of the savanna while the remaining area is completely without tree cover and that the trees do not cast shadows onto the grass surrounding them. Since this method cannot account for light trapping due to the macrostructure of the vegetation [*Federer*, 1971; *Dickinson*, 1983], these weighted-average albedos generally overestimate the albedo of nonhomogeneous vegetation canopies.

*Kimes and Kirchner* [1982] devised a model that explicitly considers horizontal inhomogeneity. A modified version of the Kimes-Kirchner model has been used to estimate canopy albedos for natural vegetation by integrating the directional reflectances over the hemisphere [*Rowe*, 1988, 1991]. As in the Kimes-Kirchner model, the vegetation canopy is represented by a module that [*Kimes and Kirchner*, 1982, p. 4122] "characterize[s] the basic structural characteristics of the scene without repetition." The landscape to be simulated is first divided into modules defined by the user. Module size is dependent on the symmetry of the landscape; landscapes with highly repetitive structure (such as row crops and orchards) can be represented by smaller modules than can landscapes with less structure (such as forests or human-built environments). This module is divided horizontally and vertically into cells. These cells contain the components (e.g., leaves, branches, trunks, open space) that comprise the landscape. Associated with each cell is the information necessary to determine the interaction of radiation with the contents of that cell (i.e., the area density, angular distribution, spatial dispersion and optical properties of leaves, branches, etc.). Two scales of data are thus required to define the vegetation canopy for this model: (1) the large-scale structure of the canopy necessary to determine the size of the module and the cell contents and (2) the small-scale distribution of the vegetation components within each cell and their corresponding optical properties. Then, a ray-tracing method similar to that of *Cooper et al.* [1982] can be extended to this three-dimensional module.

The multistream, numerical model is able to simulate the well-documented diurnal variation in albedo caused by changing solar zenith angle as well as the variation of albedo under different distributions of incident radiation [*Rowe*, 1988, 1991]. Model-simulated albedos of natural vegetation types, however, are often different in magnitude than those reported in the literature for those vegetation types. These differences can be attributed to errors in the model formulation, errors in the canopy parameterization, errors in the observed albedos, architectural differences between the vegetation canopy for which albedo was reported in the literature and the modeled canopy, or some combination of these factors. In spite of these problems, *Rowe* [1988, 1991, 1993] has shown that the numerical model is able to produce albedo estimates comparable to observations for over 30 natural vegetation types. Comparison of the albedos estimated by the Kimes-Kirchner multi-stream model to those derived from a two-stream model that can be solved analytically for horizontally homogeneous canopies has shown the relative accuracy of the numerical model to be quite high [*Dickinson et al.*, 1987*a*, *b*].

The following section gives a brief outline of the albedo model; a more complete description is given by *Rowe* [1988, 1991].

## MODEL DESCRIPTION AND PROCEDURES

Radiative flux can arise from and be scattered into an infinite number of directions, making a full three-dimensional ray-tracing algorithm computationally prohibitive. To avoid this problem, the algorithm divides the spherical coordinate system into a finite number of sectors and radiation is assumed to propagate along vectors connecting the origin with the midpoints of these sectors. These midvectors define the set of all possible directions for radiant flux in the model, and all flux in a given sector is assumed to propagate along the midvector of that sector.

Interactions between shortwave radiation and the canopy are determined by following the path of the radiation through the cells that comprise the vegetation canopy module. On the basis of the information about the components of each cell, radiation either passes through the cell undisturbed or interacts with the vegetation elements. When radiation encounters a canopy element, a portion of the radiant flux is absorbed by the element and the remainder is scattered. Flux that is unattenuated by the foliage in the cell continues along the same radiation flux vector into an adjacent cell. This process continues until the flux vector reaches the lowest layer of cells. At this point, any unattenuated flux leaving through the bottom of this layer will strike the underlying surface and either be absorbed or scattered upward (i.e., reflected). This process is repeated until every incident radiation flux vector striking each cell of the uppermost layer in the module has been traced from the canopy top to the underlying surface.

Scattered flux arising from each cell in which an interaction occurred as well as flux reflected from the substrate is considered next. All scattered flux is assumed to originate from the center of the cell in which scattering took place or, for scattering from the substrate, from the center of the lower surface of the bottom cell.

Once the scattered fluxes for a canopy or substrate cell have been distributed among the midvectors, these vectors are traced through the module and their interaction with other cells are calculated. Fluxes exiting the module through the sides are assumed to enter an adjacent module while an identical, both in magnitude and direction, radiation flux vector enters the module under consideration from the opposite side. Thus no flux can be lost through the sides or bottom of the module, only through the top.

All scattered fluxes arising from every canopy and substrate cell are traced in this manner until they exit the canopy top or strike the underlying surface. Fluxes exiting the module through the top are accumulated. This process of tracing the scattered fluxes is continued until no radiation flux vector within the module has a magnitude greater than a predetermined threshold. Finally, the accumulated above-canopy, upward directed flux is divided by the total incident flux to yield the module albedo.

While the modified ray-tracing algorithm employed in this model is, in practice, no more than an elaborate bookkeeping procedure and will not be discussed further, the treatment of the interaction of radiation with the foliage elements in a cell requires some elaboration.

As radiation enters the top of the vegetation module along a source vector, it may interact with the vegetation elements contained in any cell through which it passes. The probability, $P_0(\phi,\theta)$, that radiation will pass through a cell without striking a foliage element is expressed as

$$P_0(\phi,\theta) = \begin{cases} \exp[-LG(\phi,\theta)D] & F_d=0,\ \text{random dispersion} \\ \exp\{(L/F_d)\ln[1-G(\phi,\theta)D\ F_d]\} & F_d>0,\ \text{regular dispersion} \\ & F_d<0,\ \text{clumped dispersion} \end{cases} \tag{1}$$

where L is the foliage area density ($m^2\ m^{-3}$) of foliage elements per unit canopy volume, D is the path length of the radiation flux vector through the cell (m), and $G(\phi,\theta)$ is the mean projection of unit foliage area in the direction of the radiation flux vector with azimuth $\phi$ and elevation $\theta$ [*Nilson*, 1971]. This projection function, $G(\phi,\theta)$, is dependent on the angular distribution -- inclination and azimuth -- of the foliage elements and the direction of the radiation flux. If there is no preferred azimuth for the foliage orientation [*Ross*, 1975], the projection function is dependent only on the foliage inclination angle distribution and the elevation of the radiation flux vector. A further simplification can be made by assuming an inclination angle distribution appropriate to the canopy. Three common assumptions are (1) horizontal foliage, (2) vertical foliage, and (3) uniformly distributed foliage. The projection functions for these inclination angle distributions are given by

$$G(\phi,\theta)=\begin{cases}|\sin\theta|, & \text{horizontal}\\ 2\cos\theta/\pi, & \text{vertical}\\ 1/2, & \text{spherical}\end{cases} \tag{2}$$

When a specified foliage inclination distribution is used in conjunction with the assumption of azimuthal independence, the projection function is dependent only on the elevation angle of the radiation flux vector, $\theta$. Substituting $G(\phi,\theta)$ into the appropriate probability of gap function (1) determines the probability that the radiation flux will pass through the cell without striking any foliage element. Thus, the proportion of flux contained in the radiation flux vector that passes through the cell can be expressed as $P_0(\phi,\theta)$, while the proportion of the flux that is attenuated -- either absorbed or scattered -- is given by $[1-P_0(\phi,\theta)]$. If the foliage absorption coefficient is $a_f$, then the proportion of the flux that is absorbed is $[1-P_0(\phi,\theta)]a_f$, while $[1-P_0(\phi,\theta)](1-a_f)$ is the proportion scattered. With the additional assumption that the spatial dispersions of the different types of foliage are independent of one another [*Norman and Jarvis*, 1976], the computation of successive attenuation of the radiant flux could be extended to any number of foliage components (e.g., thorns, flowers, fruit). In the current model, only leaves and stems are included so that, if F is the magnitude of the radiation flux vector as it enters the cell, then

$$\begin{aligned}A_l&=F[1-P_0(\phi,\theta)]a_l\\ S_l&=F[1-P_0(\phi,\theta)](1-a_l)\\ F'&=FP_0(\phi,\theta)\end{aligned} \tag{3}$$

are the fluxes absorbed ($A_l$), scattered ($S_l$) and unattenuated ($F'$) by leaves while

$$\begin{aligned}A_s&=F'[1-P_0(\phi,\theta)]a_s\\ S_s&=F'[1-P_0(\phi,\theta)](1-a_s)\\ F''&=F'P_0(\phi,\theta)\end{aligned} \tag{4}$$

are those fluxes absorbed ($A_s$), scattered ($S_s$) and unattenuated ($F''$) by stems. Summation of the above terms yields the initial flux F, showing that the model conserves energy.

If only a single module were being considered, it would be necessary to know the radiation field surrounding the module on all sides and above the canopy. The model avoids this problem by assuming that the canopy is composed of adjacent modules that interact with the incident radiance in the same manner as the module being simulated; that is, the landscape is comprised of infinitely repeating modules. When radiation is predicted to exit one side of the module, an equivalent -- in direction and magnitude -- flux from an adjacent module enters the opposite side. Thus radiation can enter and exit the canopy only through the top surface of the uppermost cell layer.

## SIMULATIONS OF CANOPY ALBEDO

Savanna vegetation consists of two distinct components -- a nearly continuous understory of grass and a discontinuous upper story of trees. The trees can be distributed in a variety of patterns -- from scattered, individual trees to trees arranged in clumps. These features of the savanna make it an ideal landscape to demonstrate the importance of considering landscape heterogeneity when modeling land surface albedos. Using the canopy albedo model described above, an estimate of the albedo of a horizontally homogeneous grass canopy and a separate estimate of the albedo of a horizontally homogeneous tree canopy can be made and then combined as a weighted average to yield an approximation of the albedo of a savanna landscape. The same model can also provide estimates of savanna albedo by explicitly considering the distribution of trees across the landscape. By using the same model, cell parameters (i.e., leaf physical and optical properties) and substrate properties for both the homogeneous canopy-weighted average method and the heterogenous canopy method, any albedo differences that result should be attributable to the different specifications of the overall architecture (i.e., the spatial arrangement of cells) of the canopy.

Simulations of canopy albedo were carried out for eight different vegetation modules -- homogeneous grass cover (scenario $A_1$), homogeneous tree cover with grass understory (scenario $A_2$), and six heterogeneous canopies (scenarios B-G) each with a complete grass understory and a different distribution of trees covering 25 percent of the ground surface (Figure 1). Results from the two homogeneous scenarios ($A_1$ and $A_2$) are combined as a weighted average to give an estimate of savanna albedo and are then compared to the results from the heterogeneous scenarios.

For each cell containing vegetation, the model requires the following data: leaf and stem area densities; leaf and stem shortwave absorption coefficients; leaf and stem dispersion coefficients; leaf and stem backscatter parameters; and leaf and stem inclination angle distributions. In addition, the absorption coefficient for the substrate must be defined. The effects of stems on radiation transfer in the canopy were not considered for any of the scenarios to simplify the computations, and leaf and substrate properties were held constant for all scenarios (Table 1). Leaves were assumed to be dispersed randomly throughout each cell containing foliage regardless of vegetation type. Grasses were assumed to have a vertical, but no preferred azimuthal, orientation while trees leave were assumed to have a uniform, or spherical, orientation. Grasses were specified to have a lower absorptance than tree leaves, but tree leaves were specified to have a greater proportion of backscattered radiation. These characteristics are typical of tree leaves and grasses found in savanna regions. The substrate absorption coefficient was assigned a value of 0.75 -- representative of many soils [*Sellers*, 1965; *Oke*, 1987; *Rosenberg et al.*, 1983] and characteristic of plant litter.

## RESULTS

Estimates of canopy albedo for each scenario were made for direct radiation incident on the module from 49 different directions -- at zenith angle increments of 20° from the zenith and at azimuth angle increments of 30° from north (Figure 2). It is immediately evident from the results of these simulations that there are obvious and significant differences among the scenarios.

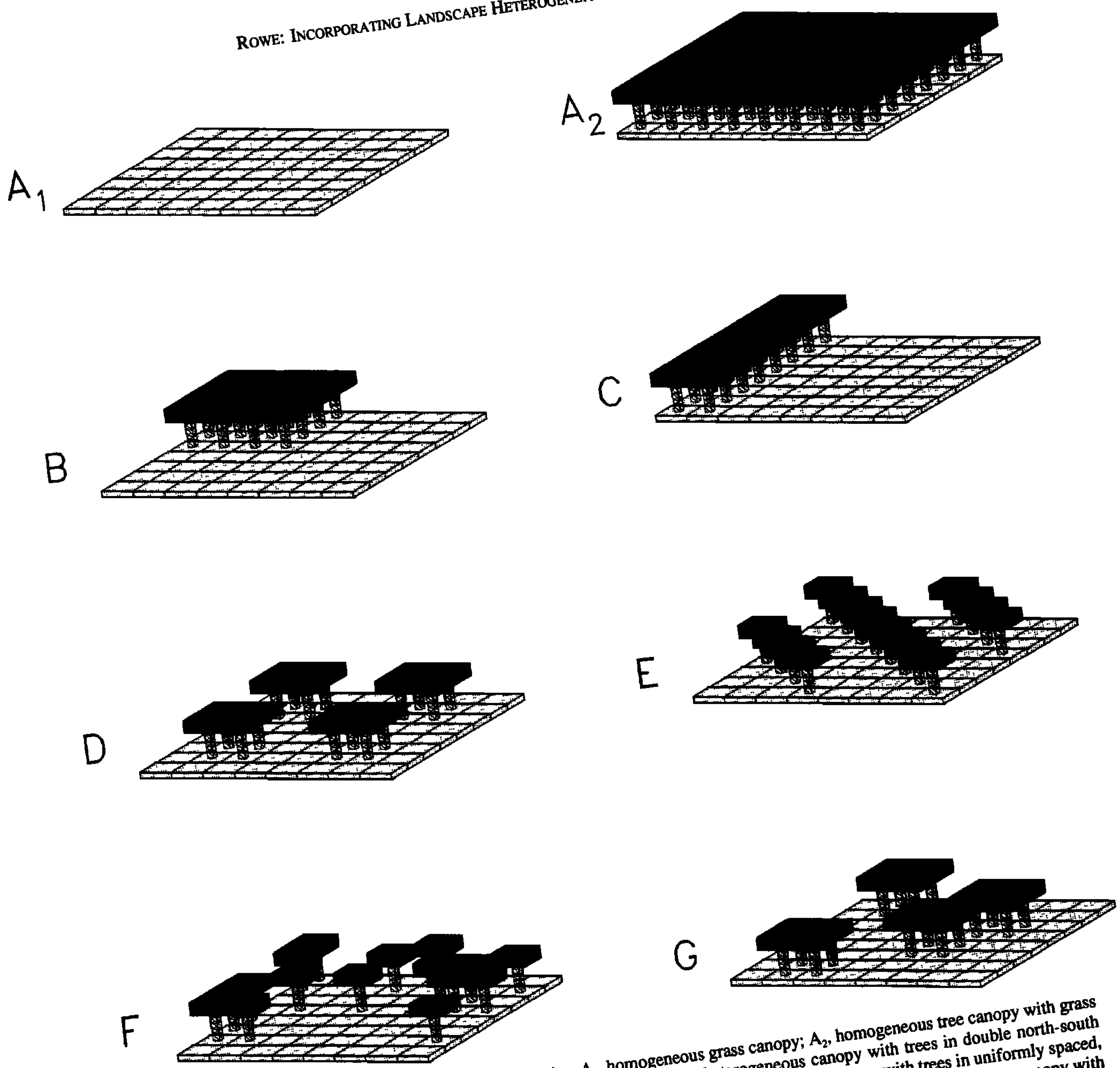


Fig. 1. Schematic representations of the canopy modules: $A_1$, homogeneous grass canopy; $A_2$, homogeneous tree canopy with grass understory; B, heterogeneous canopy with trees in single large clump; C, heterogeneous canopy with trees in double north-south row; D, heterogeneous canopy with trees in four uniformly spaced clumps; E, heterogeneous canopy with trees in uniformly spaced, single northwest-southeast rows; F, heterogeneous canopy with randomly distributed individual trees; G, heterogeneous canopy with four randomly spaced clumps of trees.

TABLE 1. Vegetation Characteristics used to Describe the Canopy Modules

| | Value |
|---|---|
| Module size | 32 x 32 x 8 m (N-S; E-W; vertical) |
| Cell dimensions | 4 x 4 x 1 m (N-S; E-W; vertical) |
| Grass Canopy Characteristics | |
| Leaf absorption | 0.35 |
| Leaf backscatter | 0.50 |
| Leaf area density | 2.60 $m^2m^{-3}$ |
| Vertical leaf orientation distribution with azimuthal symmetry | |
| Randomly dispersed leaf elements | |
| Tree Canopy Characteristics | |
| Leaf absorption | 0.50 |
| Leaf backscatter | 0.95 |
| Leaf area density | 0.91 $m^2m^{-3}$ |
| Uniform leaf orientation distribution | |
| Randomly dispersed leaf elements | |
| Substrate Characteristics | |
| Substrate absorbtance | 0.75 |

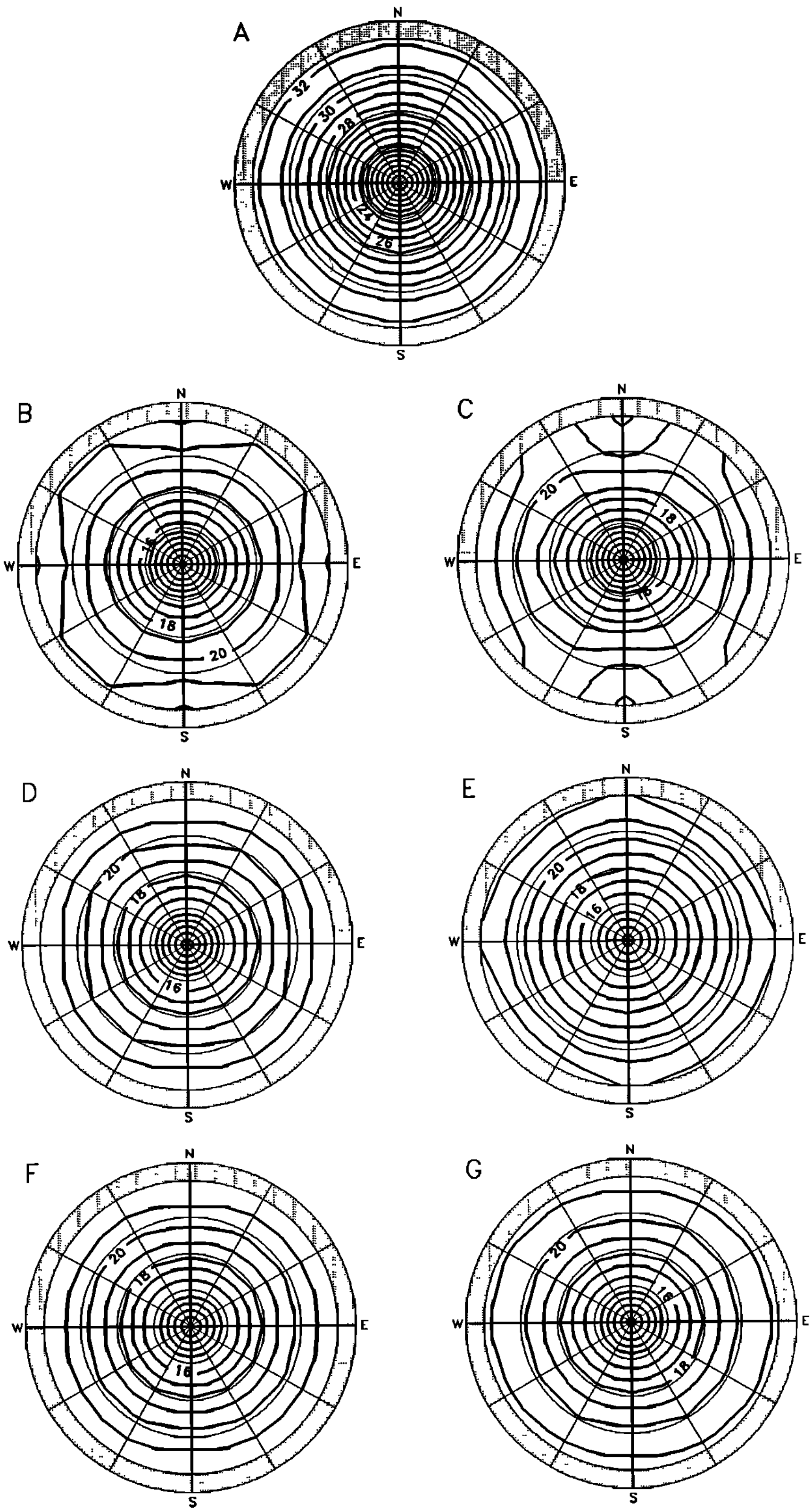


Fig. 2. Estimates of canopy albedo for each of the scenarios shown in Figure 1 for direct radiation originating from different zenith angles and azimuths. Estimates were not made for zenith angles greater than 80° (shaded).

First, the albedo estimates for the homogeneous canopy-weighted average scenario are higher, except when the incident radiation arises from the zenith, than for any of the heterogeneous scenarios. Second, the homogeneous canopy-weighted average scenario albedos increase monotonically with increasing zenith angle while the heterogeneous scenarios all exhibit a minimum when the incident radiation originates from 20° off the zenith. Finally, the homogeneous canopy-weighted average scenario does not exhibit any albedo variation with respect to the azimuth of the incident radiation. The heterogeneous scenarios all exhibit some degree of azimuthal variation, dependent on the distribution of trees across the module.

The generally higher albedos resulting from the homogeneous canopy-weighted average method as well as the difference in trend with respect to zenith angle are the result of ignoring two important characteristics of the interaction of radiation with heterogeneous canopies. The first of these is light trapping by the macrostructure of the vegetation [*Dickinson*, 1983]. This effect occurs when radiation reflected from vegetation at lower levels of the canopy (e.g., the grass canopy) does not contribute to the radiation reflected by the landscape because it interacts (i.e., is absorbed or further scattered) by vegetation at higher levels in the canopy (e.g., the trees). Light trapping will reduce the albedo of the heterogeneous scenarios compared to the homogeneous canopy-weighted average scenario since the latter has no interaction between the landscape components. The second factor not considered by the homogeneous canopy-weighted average method is the shading by taller vegetation of adjacent open areas at zenith angles greater than zero. By decreasing the radiation incident on the lower level vegetation, reflection from that surface is reduced. This will reduce the albedo of the landscape, especially if the lower level vegetation is more reflective than the taller vegetation. Since there is a general inverse relationship between vegetation height and albedo [*Stanhill*, 1970], this is likely to be a common occurrence. Except when the radiation arises from the zenith, these effects combine to dramatically reduce the heterogeneous scenario albedo compared to that for the homogeneous canopy-weighted average scenario (Figure 3). When radiation originates from the zenith, there is no shading of adjacent open areas and only light trapping reduces the albedo. For the scenarios investigated here, heterogeneous scenario albedos are higher than the homogeneous canopy-weighted average scenario when only zenithal radiation is considered.

Because the homogeneous canopy-weighted average method considers only horizontally homogeneous vegetation canopies, there can be no dependence of albedo on the azimuth of the incident radiation (Figure 2*a*). This is true regardless of the model used to compute albedos for the multiple homogeneous canopies that are used to define the landscape. When landscape heterogeneity is explicitly characterized and incorporated into an albedo model, albedo variations due to the azimuth of the incident radiation can be modeled. These azimuthal variations are greatest when the upper story (i.e., trees) is grouped into one large cluster (Figures 2*b* and 2*c*). As the trees are distributed more widely through the module (Figures 2*d* and 2*e*) the azimuthal variation

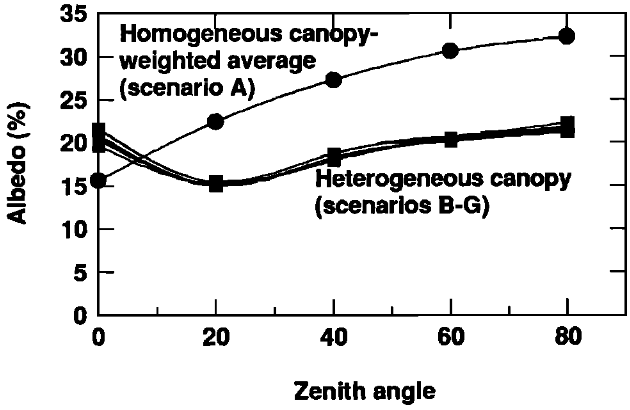


Fig. 3. Albedo variation with zenith angle of incident radiation. Estimate for heterogeneous canopies (scenarios B-G) are averaged over all azimuths.

lessens but is still apparent. Trees distributed randomly -- either as individual trees or small clumps -- exhibit nearly azimuthally invariant albedos (Figures 2*f* and 2*g*). Azimuthal variation is caused by the shading effect described above and the proportion of the grass cover that is shadowed. When the trees are grouped together, the proportion of grass in shadow is more dependent on the zenith angle and azimuth of the incident radiation than when the trees are distributed more widely. Moreover, the azimuthal variation exhibits symmetry suggesting the symmetry of the tree distribution. Since for a random tree distribution, some trees might shade more of the grass cover while others may shade less (at any one azimuth), little or no azimuthal variation of albedo remains.

## CONCLUSIONS

*Dickinson et al.* [1990] specified three criteria that models of land surface albedo for GCMs should satisfy. An adequate model (p. 111) "should be based (1) on simple expressions; (2) on the underlying radiative transfer processes at the surface; and (3) on an integration over solid angle of an expression satisfying (1) and (2) for the bidirectional reflectance of solar radiation from the surface." They conclude that a two-stream model meets these criteria and provides accurate estimates of canopy albedo for homogeneous canopies. Unfortunately, little of the Earth's surface can be characterized as homogeneous and it has been demonstrated here that explicit consideration of heterogeneous canopy architecture has a significant impact on albedo estimates. The numerical, multistream model employed here also meets the three criteria of *Dickinson et al.* [1990] although, because of the geometric discretization necessary to characterize the heterogeneity of the canopy, considerably more computation is required and the specification of canopy architecture is much more difficult. These factors preclude the use of this type of model directly as part of GCM simulations. However, offline computations could be made and the results used to develop parameterizations of albedo for heterogeneous canopies as a function of the spatial distribution of incident radiation (i.e., the solar zenith and azimuth angles and the ratio of diffuse to direct) for any number of vegetation types.

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