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A three-dimensional analytic model for the scattering of a spherical bush

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[1] Advanced climate models require a more realistic description of canopy radiation with reasonable computational efficiency. This paper develops the mathematics of scattering from a spherical object conceptualized to be a spherical bush to provide a building block that helps to address this need of climate models. It is composed of a homogeneous distribution of individual smaller objects that scatter isotropically. In the limit of small optical depth, incident radiation will scatter isotropically as the sum of that scattered by all the individual scatterers, but at large optical depth the radiation leaving the spherical bush in a given direction is reduced by mutual shadowing of the smaller objects. In the single scattering limit, the scattering phase function and so the albedo are obtained by simple but accurate analytic expressions derived from analytic integration and numerical evaluation. Except in the limit of thin canopies, the scattering and hence albedos are qualitatively and quantitatively different than those derived from 1-D modeling.

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1. Introduction: The Importance of Addressing Three-Dimensional Radiation in Climate Models

[2] The surface energy, water and carbon balances at the terrestrial surface are controlled by absorption of incident solar radiation. Climate models currently describe this absorption in terms of a canopy architecture that can be highly unrealistic and inaccurate. If they constrain their absorption of radiative energy by accurate satellite observations of albedo [e.g., *Lucht et al.*, 2000; *Schaaf et al.*, 2002; *Wang et al.*, 2004; *Tian et al.*, 2004; *Liang et al.*, 2005; *Lawrence and Chase*, 2007], their solar forcing over the land surface should be of comparable accuracy. However, details as to how this absorbed radiation is partitioned between various components of the terrestrial system may still be determined very inaccurately, possibly resulting in deficiencies of the climate simulation.

[3] For example, forests overlying snow have been assumed through their contribution to absorption to increase surface temperatures from that of a forest free surface [e.g., *Bonan et al.*, 1992; *Betts et al.*, 2007] and so contribute to the melting of the snow. However, such a forest is also directly removing incident solar energy from the snow and so, without some further energy exchange mechanism such as downward sensible and long-wave fluxes, would be shadowing and cooling the snow, not melting it. Semiarid or other sparsely vegetated systems have bushes that shade a much larger area than that of their vertical projection, an effect that can only be accounted for in a three-dimensional (3-D) geometry. Widely spaced individual bushes have no radiative effect on each other and can be treated in isolation, the topic of this paper.

[4] Detailed numerical treatments of the canopy radiation in complex 3-D geometries have been developed by various authors, mostly for application to remote sensing [e.g., *Myneni et al.*, 1995; *Knyazikhin et al.*, 1998; *Lewis*, 1999; *Qin and Gerstl*, 2000; *Kimes et al.*, 2002; *Li et al.*, 1995], but these treatments have not been translated into simple rules suitable for climate models. Rather, 1-D treatments [e.g., *Dickinson*, 1983; *Sellers*, 1985] have been popular because they are simple enough to require the evaluation of at most a few exponentials. An overall objective of our research is to establish how much of canopy radiation in 3-D can be described with comparable simplicity. Radiation within a canopy is, in principle, complicated by the multiple reflections between canopy elements and with the underlying surface. However, over the visible part of the solar spectrum, the contributions from multiple scattering are small. They can be taken as a separate component to be added to the single scattering of a canopy [e.g., *Pinty et al.*, 2006; *Knyazikhin et al.*, 2005]. Radiation leaving a canopy is completely characterized by its scattering phase function Ψ, i.e., given by the product of the phase function provided by individual leaves [cf. *Pinty et al.*, 2006] and the contribution from the shading by the distribution of leaves.

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