A Stochastic Formulation of Radiative Transfer in Clouds

G. L. Stephens, P. M. Gabriel, K. F. Evans, and D. Duda
Colorado State University
Department of Atmospheric Science
Ft. Collins, CO 80523

Introduction

The research conducted as part of this project breaks down into three broad areas:

- deterministic radiative transfer
- remote sensing
- stochastic radiative transfer.

The approach pursued in this research employs different forms of radiative transfer models in one, two, and three dimensions in an attempt to understand radiative transfer in clouds with realistic spatial structure and to determine the key geometrical parameters that influence this transfer. A key focus is understanding the relative importance of these geometrical effects in contrast to the microphysical effects of clouds. The main conclusion is that geometry has a profound influence on all aspects of radiative transfer and the interpretation of this transfer.

Deterministic Radiative Transfer

Our research on radiative transfer has produced three different formulations and solutions of the radiative transfer problem. The first is an efficient Monte Carlo model (O'Brien 1992) that has been used as a benchmark for testing the other two numerical models. The two different numerical solutions are in excellent agreement with Monte Carlo results. These models are discussed in detail by Gabriel et al. (1993) for the Fourier-Riccati method and Evans (1993) for the Spherical Harmonic Spatial Grid method.

The Fourier-Riccati model was used to study the effects of geometry on solar heating rate. The essential conclusions of this work are given in Figure 1, showing the horizontal disposition of the heating at different depths in the cloud compared with the plane parallel heating. The heating is highly distributed and significantly exceeds the plane parallel values in the densest regions of the cloud. The two panels differ in the microphysics assumed in the simulation. Clearly, both microphysics and geometry affect the heating in important ways.

Remote Sensing

We also examine the effects of geometry on spectral reflectance and, using procedures published in the literature, interpret these effects in terms of retrieved optical properties of clouds. An example of this work is presented in Figure 2, which shows the bispectral plot of radiances derived from a simulation of radiative transfer through a 2D variable cloud. The particle size distribution was fixed in this cloud, and only number concentration was varied (thus, the effective radius was also fixed at all levels).

The scatter of points of Figure 2 is a direct result of the geometrical influences on spectral reflectances. This scatter is erroneously interpreted as changes in both optical depth and effective radius, the former varying by as much as 20% and the latter by as much as 30% to 50%.

Stochastic Radiative Transfer

These and many other studies clearly indicate that geometrical factors profoundly influence the transfer of radiation through clouds. It is unlikely that all of the relevant scales of spatial variability will be resolved in climate models, or even cloud models. Furthermore, it is the mean radiative quantities and not the details of the radiation field that are important for the climate system.

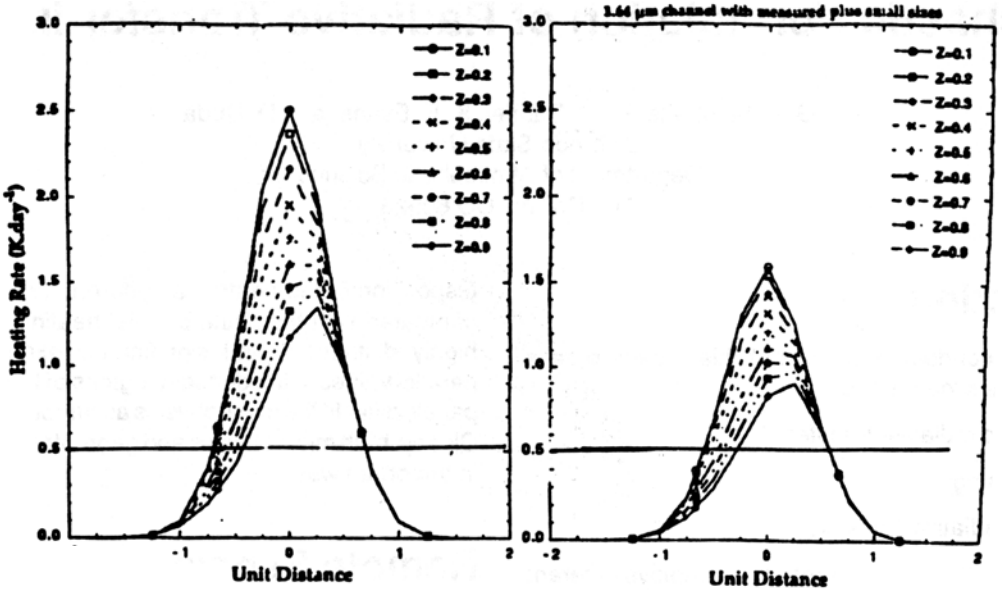

Figure 1. Two-dimensional heating rates calculated by Fourier-Raccati method. Cloud has a Gaussian extinction function and is illuminated by 1.64 micrometer radiation at a solar zenith angle of 30 degrees. Solid horizontal line is the heating rate as calculated by a plane-parallel model using a domain averaged optical depth of 1.0. Differences in figures are due to differences in the microphysics. Microphysics of the cloud in the left figure is based on measurements where the smallest resolvable particle is approximately 17 micrometers. The cloud on the right includes small particles. The particle size is distributed according to a gamma distribution.

The question remains as to what is the relevant structure information and how this information should be incorporated into radiative transfer. Stochastic transfer methods attempt to address these questions by investigating the radiative effects of ensembles of cloud structures described by probability distributions. The previous work on stochastic radiative transfer has been limited in its applicability to the atmosphere by assumptions such as small amounts of variability, no internal structure in clouds, or inappropriate spatial distribution functions.

We have developed a new method of stochastic radiative transfer that applies to any sort of spatial variability in clouds (Evans 1993). The new method is based on the backward Monte Carlo solution of radiative transfer, using O'Brien's (1992) method. The radiance or flux exiting a surface is expressed as an order of scattering series. Each scattering is associated with an integral over transmission along a path and an angular integral over direction to the next path.

The fundamental idea behind this new method of stochastic radiative transfer modeling is to do backward Monte Carlo integration of the order of scattering integral with additional integrations over probability distributions of path lengths. The spatial variability information is expressed in path probability density functions (pdf). With the assumption of homogeneous and isotropic statistics, a single path pdf has the form f(s|T), which is the conditional density of distance(s) given transmission (T). Since successive paths are not independent, higher order information such as the two-path pdf f(s_2|T_2,s_1,T_1) is needed. There is a hierarchy of approximations based on the order and form of the path pdf's.

The accuracy of these approximations was tested by computing deterministic Monte Carlo radiative transfer in many realizations of 3D isotropic lognormal-multifractal extinction fields. In simulations of thermal radiative transfer in cirrus clouds and solar radiative transfer in boundary

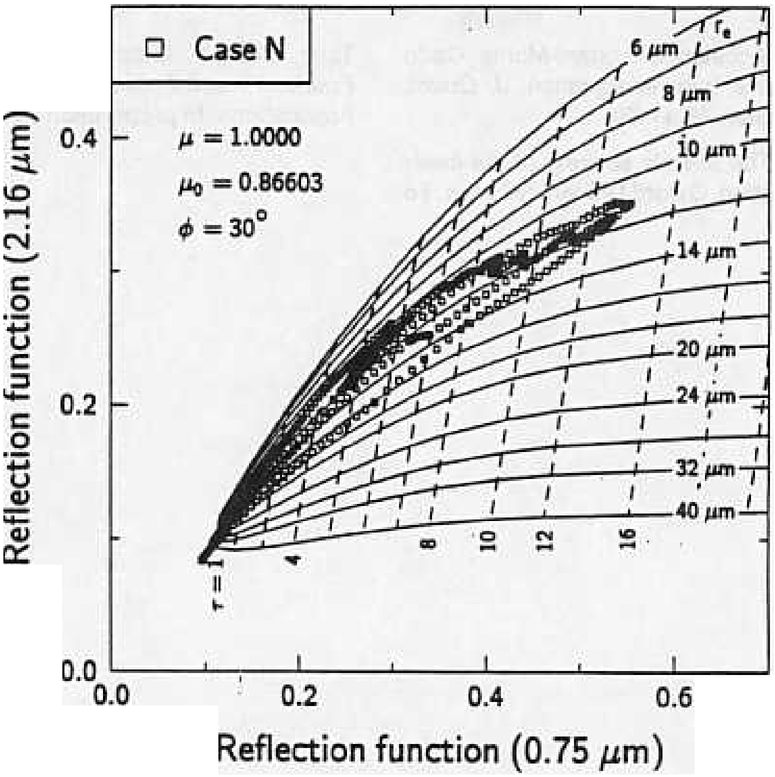

Figure 2. A bispectral scatter plot of simulated reflectance on a plane-parallel $\tau_e\tau$ grid. The scatter arises solely from geometrical effects.

layer clouds, each with a range of variability, the stochastic method with two-path pdf's gave accurate mean flux results, while use of the single-path pdf's usually did not. Besides providing a practical and general method of stochastic radiative transfer, this work also indicates what cloud structure information is important for radiative transfer. Path pdf's can be obtained from in situ measurements using aircraft, as well as from cloud radars and lidars. Such observations combined with further modeling should lead to radiation parameterizations for climate models that incorporate the effect of heterogeneities in clouds.

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