A Study of Monte Carlo Radiative Transfer Through Fractal Clouds

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Abstract

An understanding of radiation transport (RT) through clouds is fundamental to studies of the earth's radiation budget and climate dynamics. The transmission through horizontally homogeneous clouds has been studied thoroughly using accurate, discreet ordinates radiative transfer models. However, the applicability of these results to general problems of global radiation budget is limited by the plane parallel assumption and the fact that real cloud fields show variability, both vertically and horizontally, on all size scales. To understand how radiation interacts with realistic clouds, we have used a Monte Carlo radiative transfer model to compute the details of the photon-cloud interaction on synthetic cloud fields. Synthetic cloud fields, generated by a cascade model, reproduce the scaling behavior, as well as the cloud variability observed and estimated from cloud satellite data.

Introduction

The goal of this experiment is to simulate radiation through clouds using a scaling field to reproduce the variability of the cloud optical thickness at small-scale length. The scaling fields are generated using cascade processes characterized by a stable distribution specified by two parameters: α and C_1 (see Figure 1). A Monte Carlo model was used to compute the interaction (scattering and absorption) between photons and cloud droplets. The radiance and flux fields were obtained from two realizations of the cloud field, both having the same values α and C_1.

This experiment is meant to investigate two important questions: 1) To what extent are the scaling and statistical properties of the original scaling fields of the cloud optical depth preserved in the resultant radiation fields? and

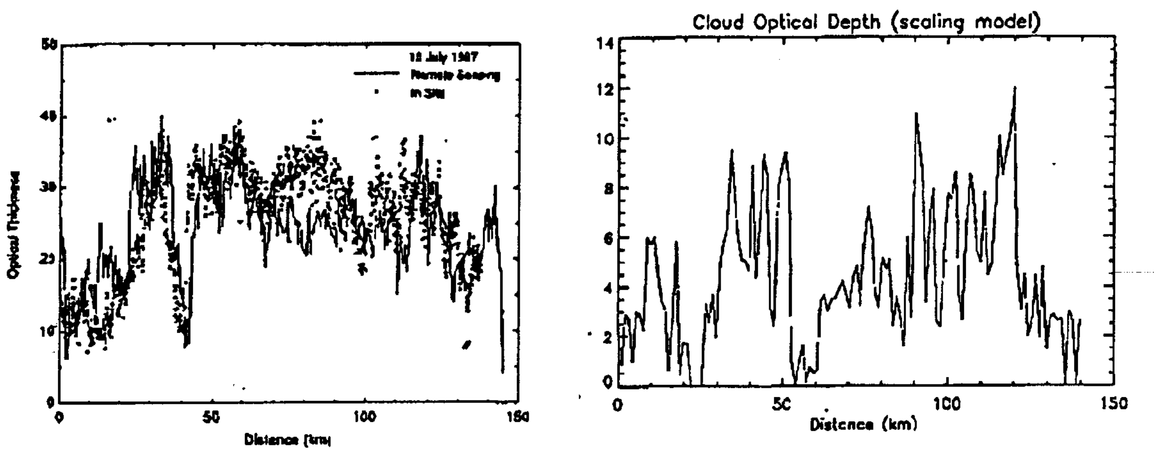

Figure 1. Variability of cloud optical depth derived from remote sensing and in sit u measurements (left) (taken from Nakajima and King 1991) and from the scaling model (right) with values α = 1.3 and C_1 = 0.1 (values corresponding to those observed for cloud satellit e radiance).

2) How well can they be derived from the observed radiance and flux fields? These issues are fundamental to the question of how large-scale statistical properties of cloud radiance fields are to be used to describe smaller scale macro- or micro-physical parameters.

Traditional methods to derive cloud properties from satellite imagery have relied on the so called "independent pixel" approximation. In this approach it is assumed cloud properties are constant and horizontally homogenous within each pixel. This assumption permits the use of plane parallel radiative transfer theory to derive the optical depth and other cloud properties within each picture element. This technique has been used within the International Satellite Cloud Climatology Project (ISCCP) to derive global cloud properties at ~km-scale resolution.

DISORT Calculations

As a baseline with which to compare the Monte Carlo runs, we have used the independent pixel approximation together with a discrete ordinate radiative transfer (DISORT) model to compute the radiant intensity received by a satellite sensor. In our simulations the nadir viewing angle and solar zenith angle are both set to zero.

For both the Monte Carlo and DISORT calculations, we use an ocean surface and include effects of marine aerosols with a surface visibility of 23 km. Both codes use the LOWTRAN 7 band models to compute molecular absorption. The surface albedo and aerosol distribution are assumed to be horizontally homogeneous over the entire scene. The clouds are made up of pure water droplets with a size distribution characterized by an effective radius of 8 μm. The radiative properties of the cloud droplets are computed from Mie scattering theory and are parameterized using the Henyey-Greenstein phase function. The DISORT calculation uses 20 radiation streams and 34 vertical computational layers.

In Figure 2 we show DISORT's predictions for the upwelling radiant flux at the of the top of the atmosphere (TOA) for cloud optical depths in the range 0 to 64. The Channel 1 band is characterized by conservative photon scattering, whereas the Channel 2 band displays significant water vapor absorption.

The Monte Carlo Model

The Monte Carlo method is essentially a direct simulation of the physical processes involved in radiative transfer where the path of a photon is described by probability

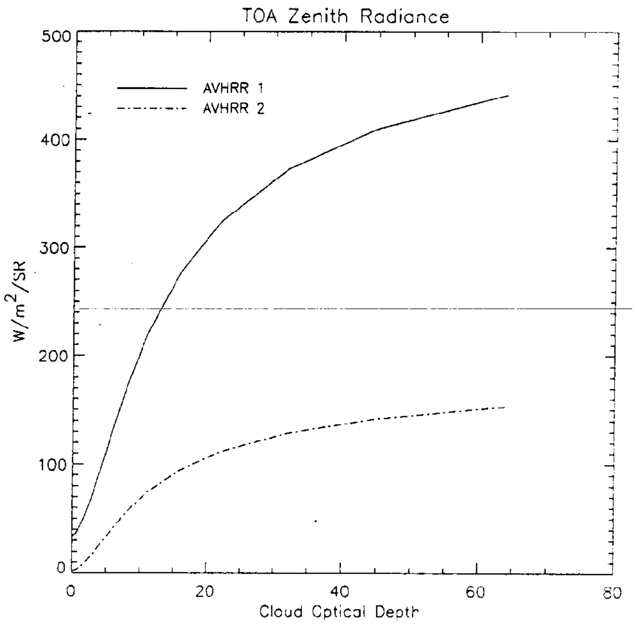

Figure 2. The top of atmosphere (TOA) radiance from DISORT (plane parallel) for two visible channels, 630 nm and 931 nm, representing the pass bands of the AVHRR Channel 1 and 2 detectors. Compared with Channel 1, the Channel 2 pass band is characterized by much greater water vapor absorption and nearly vanishing reflectance from the ocean surface.

functions. These functions describe the distance a photon travels before an interaction; the result of the interaction (absorption of scattering); and, if scattered, the scattering direction. The Monte Carlo model used in these simulations is designed around a 3-dimensional spatially dynamic structure. This structure provides for large, low variability cells to reduce computations and nested higher resolution cells to allow the mixing of various spatial scales. Each cell can contain any combination and concentration of gases, aerosols, and cloud droplets.

Results

Manifestation of scaling can be observed using standard spectral analysis. For instance, power spectrum of a scaling fields is given by

$$E(k) \sim k^{-\beta} \qquad (1)$$

where $k \equiv |\mathbf{k}|$ is the wave number magnitude and the scaling exponent β associated with E(k). For 2-D fields, the power spectrum is obtained by first integrating over the azimuth angle the squared modulus of the Fourier transform of the field and second by taking the statistical ensemble average (usually approximated by a sum over independent statistical samples when available).

Comparisons between the scaling behavior of E(k) for cloud optical thickness, and the radiance from both DISORT and Monte Carlo are presented in Figure 3. The power spectra of the radiance fields decrease with power laws similar to the input optical depth field. This indicates that the scaling is fairly well preserved. It also suggests that, within a multiplicative constant, the correlations are preserved by DISORT and Monte Carlo, and each have a similar distribution of the second order moments (associated with cloud optical thickness and both radiance channels) as a function of the wave number. The very similar spectral slope of DISORT's radiance and the original optical depth field are due to a low average value of the cloud optical thickness. For small values of optical depth, the radiance from DISORT is an almost linear transformation of the original cloud optical thickness.

Although the spectral slopes of the Monte Carlo radiances are close to that of the cloud optical thickness (a difference smaller than 10%), the curves are more variable (perhaps due to photon count statistics). Also, whereas the DISORT results indicate no difference in the E(k) for the two advanced very high resolution radiometer (AVHRR) channels and the optical depth, the Monte Carlo results show slightly less spectral power at high spatial frequencies for Channel 2 and more power at high frequencies for Channel 1. This result is surprising. We had anticipated that the horizontal photon transport allowed in Monte Carlo would cause lower power at high spatial frequency for both the Channel 1 and Channel 2 radiances, with perhaps less high frequency power in Channel 1 because the conservative scattering should augment the horizontal diffusion of photons. Instead, we find reduced high frequencies in the Channel 2 radiance. We have repeated this experiment on 10 different cloud optical depth samples and have consistently found steeper spectral slopes for Channel 2 vs. Channel 1. A possible explanation is that water vapor absorption is accentuated in regions of increased optical depth variability. Monte Carlo's 3-D photon diffusion allows deeper penetration of photons into regions where they can be absorbed by water vapor. Thus Channel 2 power spectra tend to be depleted at high frequencies because the regions with increased variability reflect back fewer photons.

These results, although preliminary, are suggestive of interesting 3-D effects which may have an impact on cloud retrieval algorithms that depend on the wavelength dependence of cloud reflectance. For example, the retrieval of cloud optical depth and cloud drop effective radius depends on simultaneous observations at visible and near infrared (IR) wavelengths. The enhanced absorption in the near IR brought about by increased cloud variability may distort these retrievals. In future experiments we will clarify this issue by repeating the same study over a larger number of samples and for other spectral bands. Analysis of the scaling properties in the physical (real) space will also be investigated.

Reference

Nakajima T., and M. D. King. 1991. Determination of the optical thickness and effective parts in radius of clouds from reflected solar radiation measurements. Part I: Theory, *J. Atmos. Sci.*, **48**, 735.

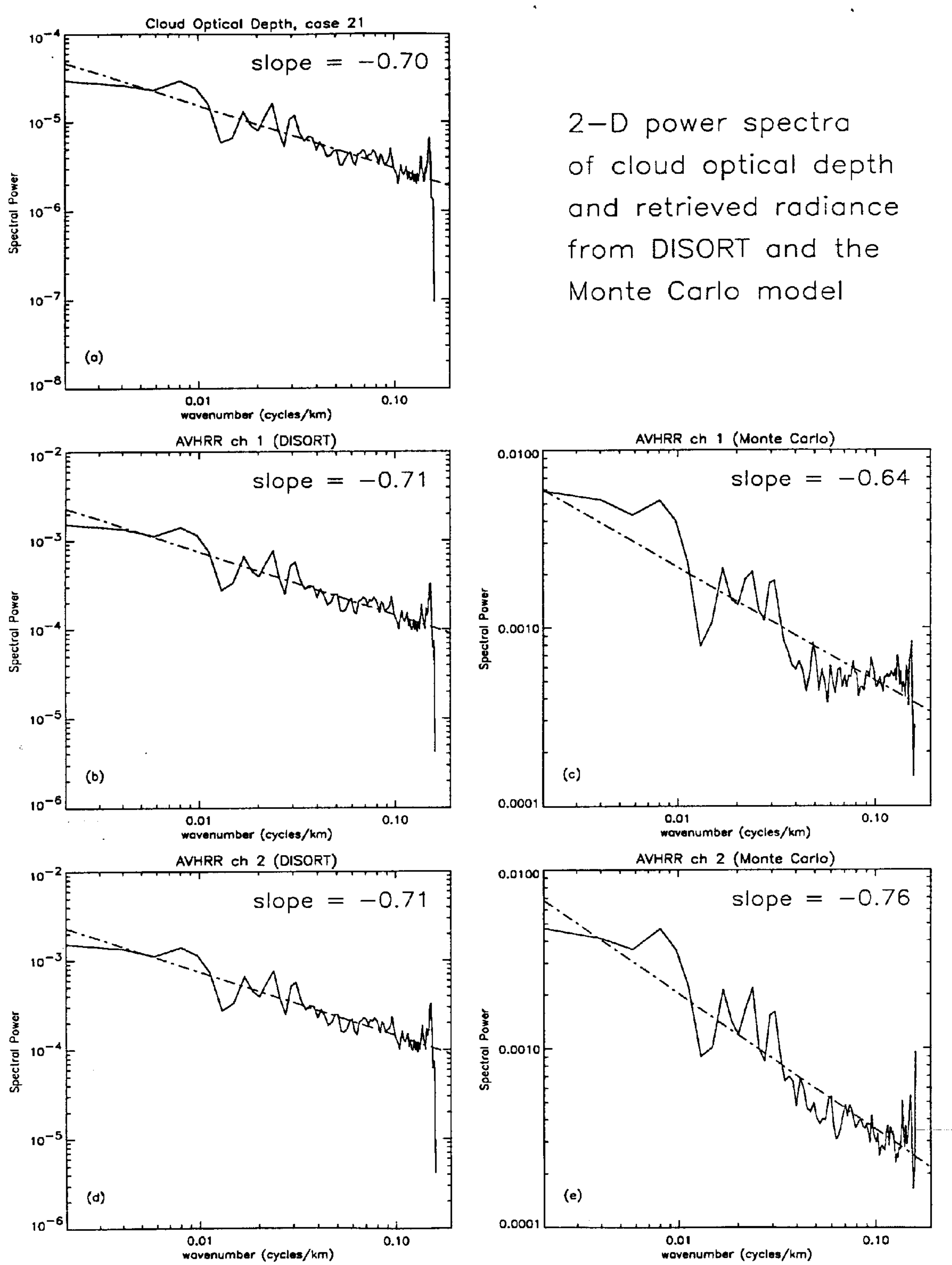

Figure 3. 2-D power spectra of a) the cloud optical depth realization, b) retrieved AVHRR Channel 1 radiance from DISORT, c) retrieved AVHRR Channel 1 radiance from Monte Carlo, d) retrieved AVHRR Channel 2 radiance from DISORT, and e) retrieved AVHRR Channel 2 radiance from Monte Carlo.