Cloud Effects on Radiation at the Top of the Atmosphere and at the Surface: Observations and Modeling Studies

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Introduction

Our project's main goal is to study the effects of clouds, particularly those with inhomogeneous spatial properties, on radiation at the top of the atmosphere and at the surface. To accomplish this goal, we use a combination of observations from space and at the surface and models to diagnose processes and predict relationships between cloud properties and radiation fields. In addition, we develop theoretical foundations for our main analysis procedure, which is based on multifractal theory and analysis techniques.

Our project is thus multi-faceted as is reflected in this abstract and our presentation. Preliminary analysis of data from the Atmospheric Radiation Measurement (ARM) Program involves computing the surface shortwave irradiance data from the Visible and Infrared Spin-Scan Radiometer (VISSR) on the Geostationary Operational Environmental Satellite (GOES), as well as estimating the multifractal properties of the cloud radiance field observed by the satellite. The analysis of non-ARM data includes satellite and in-situ observations over the Antarctic, as well as multispectral (visible, IR and microwave) satellite observations over the globe. The modeling activities encompass diagnostic studies with a number of radiative transfer codes, particularly the Discrete Ordinate model of Stamnes et al. (1988) (DISORT), and the development of a highly flexible Monte Carlo model to compute the three-dimensional (3-D) radiation field for any cloud (liquid water) distribution. In addition, a number of multifractal analyses have been performed with satellite data, and new radiative transfer simulations have been achieved.

Role of Clouds on Surface Solar Irradiance over ARM Central Site

We have developed an operational procedure to compute the downwelling and net shortwave irradiance at the surface from hourly GOES VISSR visible data over the central ARM Site at 1-km resolution. These computations are performed with a version of the simple radiative transfer model of Gautier et al. (1980) and require surface and cloud albedo. Hourly surface albedos are computed from clear brightness values obtained by applying a minimum brightness technique on a sequence of brightness values over a several day period for each pixel. Such fields will be used to investigate the effects of clouds on the spatial variability of the surface shortwave irradiance.

The spatial variability of the first mean field, computed for sixteen (16) daily values obtained in January and February 1993 is rather small with values ranging from about 100 Wm^{-2} to 140 Wm^{-2}. This result can be explained by the fact that the effects of the cloud field are rather random, when averaged over a 16-day time period. The largest values of the field are found in the northwest corner of the analyzed area and correspond to high surface albedo regions. This results from the multiple cloud-base-to-surface reflections which enhance the downwelling surface shortwave irradiance.

Multifractal Data Analysis

Atmospheric observations are characterized by extreme variability over a wide range of scale. The scaling symmetry observed in geophysical fields can be characterized with the help of multifractal dimensions. These dimensions give a complete statistical description of the geophysical fields that is scale independent. Multifractals are also characterized by their scaling exponents, and when generated by canonical cascade processes, they generally belong to specific universal classes. In this case, the scaling exponents are specified by two parameters, the Lévy index α and the codimension of the mean singularity C_1.

Modeling and statistical analysis of clouds and their associated radiance fields require knowledge of the basic length scales involved. The standard model of atmospheric dynamics involves isotropic 3-D turbulent regimes at small scales, separated by an isotropic two dimensional (2-D) turbulent regime at large scales. It is supposed that these regimes have qualitatively different types of scaling in the mesoscale that define a basic length scale separating small and large scale motions and structures. However, new ideas about generalized scale invariance lead to the simpler assumption of a single anisotropic scaling regime spanning the entire range of meteorologically significant motions; this is the "unified scaling model."

Clouds and their radiance fields provide sensitive tests of these ideas. Using Meteorological Satellite (METEOSAT), LANDSAT and Advanced Very High Resolution Radiometer (AVHRR) data at visible, IR, and near IR wavelengths, we presented the first systematic analysis of satellite cloud radiances over the ocean. By calculating energy spectra, we were able to show that over the range of ≈160 m to ≈4000 km, as predicted by the unified scaling model, these radiances display a very nearly power law form. Since wide scaling ranges will lead to multifractal statistics, this study (which must be followed up by studies of the smaller and larger scales) provides an essential justification for multifractal modeling of clouds and the associated radiative transport phenomena. In further support of the unified scaling model, we also reported on a series of recent multifractal analyses indicating that the radiance fields are special types of ("universal") multifractals also predicted by the theory.

GOES IR Radiance Field over the Central Site

Using the "Double Trace Moment" that allows direct estimate of the α and C_1 parameters, the scaling behavior of GOES IR data over the ARM site has been analyzed.

The results confirmed that the scale invariance is a fundamental feature of the atmosphere that is independent of the instrument.

With a value of α: ≈ 1.36, IR GOES data have the same degree of multifractality as the IR satellite data $\alpha \approx 1.35$ obtained from other satellite observations (e.g., AVHRR). This value is larger for IR satellite data than for visible data (α: ≈ 1.1), but smaller than for microwave satellite data (α: ≈ 1.64).

The fact that α varies with wavelength suggests that the radiances probability distributions are not the same. This finding is not so surprising, since quantities associated with each sensor may be governed by different dynamical processes. This result is important since the data analyzed are for land surface conditions, and it suggests that the analysis is not overly sensitive to the background (ocean vs. land).

Simulated and Observed AVHRR Images Over Antarctica Using Plane Parallel Clouds

We have performed a radiative transfer modeling and observational study over Antarctica with the goal of better understanding the interaction between radiation and clouds over highly reflecting surfaces. In-situ observations have been provided by ground-based spectral (corresponding to channel 1 and 2 of the AVHRR instrument) and broadband radiometers. Satellite radiances have been obtained from the AVHRR instrument on NOAA 10 and 11. To interpret the satellite observations in terms of cloud properties, we have estimated the surface albedo using the AVHRR data in clear conditions and computed the top of the atmosphere radiance that AVHRR would see under the assumption of plane parallel clouds for a number of cloud optical thicknesses. The modeling was performed with the DISORT model (Stamnes et al. 1988). One of the reasons for performing these comparisons is to test the adequacy of DISORT's plane parallel approximation over the maritime Antarctic, a region where stratiform clouds are expected to be typical.

Comparisons between observed AVHRR (Ch. 1) radiance and simulated AVHRR radiances for different cloud optical thicknesses under plane-parallel assumption were presented for two days: days 281 and 285. On Day 281, the observed satellite image displays a low radiance contrast and the appearance of full cloud coverage over most of the image. On the contrary, on Day 285, the observed satellite image displays more variability in the cloud field. The simulated data show that a very large optical thickness (far larger than that suggested by the surface instruments) is needed to reproduce the observed low contrast. An analysis of the cross section for that day further suggests that the observed radiance gradient is opposite from that simulated.

Some processes, not included in the plane parallel simulations, act to decrease the cloud radiance over snow and ice. We believe these processes are related to the clouds' 3-D geometry and expect to resolve this issue with the Monte-Carlo radiative transfer model described in the next section.

Top of the Atmosphere Simulated Radiance Field for Fractal Clouds

A Monte Carlo model has been developed. It is based on a structure of unlimited spatially variable cells capable of modeling the interactions of photons with the major radiative constituents of the atmosphere. By varying the size of individual cells, we can enhance the resolution for areas being investigated. For more homogeneous areas, a reduction in resolution lessens processing time and provides a buffer effect on the boundaries of the model structure.

Each cell can be individually addressed and assigned differing amounts and mixtures of atmospheric gases, aerosols and cloud properties. Cells in the lower boundary of the model can be assigned a multitude of complex surface features including semitransparent cells capable of simulating vegetation canopies.

Input to the model is achieved through one-, two- and three-dimensional overlays allowing the direct entry of satellite images, spatial classifications and theoretically derived cloud parameters. Dividing the Monte Carlo calculations among many processors allows numerous complex simulations to be run in relatively short time. Individual locations and trajectory vectors of photon absorption, scattering and exiting from the model's structure are all stored to provide maximum flexibility in post-run analysis.

Antarctic Cloud Properties Derived From Surface FTIR Measurements

Spectral resolved radiometric measurements of middle infrared atmospheric emission can be used in conjunction with detailed radiative transfer calculations to retrieve cloud emissivity and to estimate cloud liquid water path (LWP), optical depth, and equivalent radius of the droplet size distribution. Using a discrete-ordinates radiative transfer formulation, we have developed an algorithm to retrieve these properties from Fourier transform infrared

(FTIR) data. The algorithm has been successfully applied to a 4-month Antarctic data set provided by the CalSpace FTIR Spectroradiometer.

Radiative transfer calculations sufficient to bracket values expected in the field were performed to estimate spectral cloud emissivity for a range of cloud optical depth, liquid water content, and equivalent radius.

These calculations made use of bi-modal droplet size distributions actually observed in Antarctic clouds. A least-squares algorithm is used to choose a theoretical cloud emission spectrum that best reproduces a given measured brightness temperature spectrum. The results show marked differences in cloud emissivity between high and low overcast layers and between clouds with and without precipitation. The results also suggest that the emissivity of a maritime Antarctic cloud deck should be smaller for a given LWP than the parameterization frequently used in general circulation models.

Radiative Transfer Modeling

The simplest nontrivial scaling models of cloud heterogeneity are the monofractal models which assume the optical density is constant on a fractal set, zero elsewhere. This already leads to bulk (averaged) albedo and transmission properties which differ from plane parallel theory by factors which become arbitrarily large as the clouds get thicker. To study the transfer in the more realistic multifractal models, we developed a series of approaches: numerical simulations, orders of scattering, and radiative diffusion.

Numerical Simulations

To understand the relations between the cloud and radiation fields, we sought to statistically relate the multifractal singularities of the various fields. From a numerical point of view, this is very demanding: the existence of rare but extremely optically dense regions can lead to spurious negative intensities if the radiative transfer equations are not integrated with great care. Monte Carlo techniques avoid this problem, but require enormous numbers of simulated photons in order to yield good estimates of the internal cloud fields.

We therefore developed a robust semi-implicit scheme. This scheme was used to numerically test theoretical predictions that vertical fluctuations in an appropriately defined relative intensity can be approximately related to the horizontally averaged mean optical density. If this relationship can be substantiated by further numerical and theoretical work, it will be possible to predict the overall multifractal statistical properties of the radiation field from those of the cloud field.

Orders of Scattering Approach

The relation between cloud and radiation fields is relatively simple in two limiting situations: the optically thin (linear) regime and the optically thick regime. The latter can be tackled analytically by deriving asymptotic expansions for the scattering of various orders in the (large) extinction coefficient. In the case of log-normal multifractal clouds, we presented specific results for photon path statistics, and we indicated how to extend them using functional integration.

Radiative Diffusion

In optically thick clouds, the complex radiative transfer equation is often replaced by the much simpler diffusion equation. While there now exists a considerable body of literature concerning diffusion in monofractal systems, diffusion on multifractals is a completely new paradigm for diffusion.

Using Monte Carlo simulations, we presented the very first results. These indicate that, in spite of the existence of multifractal radiation fields, the transport is apparently dominated by a single fractal component. In addition, the resulting diffusion is systematically slower than normal diffusion ("subdiffusion"), indicating that photons tend to get "trapped" in low optical density regions surrounded by denser regions.