Evaluation of a Stochastic Radiative Transfer Model Using Ground-Based Measurements

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Introduction

Scientists have long been aware there is a need for a stochastic description of radiative transfer through media with statistically distributed parameters (Stephens 1984; Ramanathan et al. 1989; Stephens et al. 1991). This study used a shortwave stochastic band model to investigate radiative transfer through a broken cloud field for several days when low-lying fair-weather cumulus and cumulus fractus clouds were present at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) site. The stochastic model distributes clouds in a clear sky according to the statistics of the cloud field and then calculates the ensemble-averaged radiation field. A one-dimensional shortwave radiation routine used in many modern general circulation models (GCMs) is used to evaluate the performance of the stochastic model. Numerical tests are performed to assess model sensitivity and to verify the realism of several parameters. The stochastic model appears promising in its ability to predict the observed downwelling radiation under a broken cloud field relative to the two-stream model.

Theory

Stochastic theory, which is derived from linear kinetic theory, utilizes the statistics of a line. The stochastic nature of the problem enters through the statistical description of the partially cloudy atmosphere (Malvagi et al. 1993). For bimaterial statistics, the line is populated by alternating segments of two materials, in this case cloud and clear sky. The material lengths are randomly chosen from predetermined chord-length distributions. Cloud differs from clear sky in the liquid water content and radiative properties. The probability distribution function describing the distribution of cloud is the same throughout the layer. The clouds occupy on average a fraction of the volume of the cloudy layer.

Two coupled, formally exact, transport equations are used to describe particle flow in a binary statistical mixture. The source and cross sections are considered to be non-stochastic in that they are given as a function of the material. It is important to note that cloudy and clear sky can have different statistics. However, for these calculations, the restricted problem of three-dimensional clouds embedded in a planar layer is considered. This limits the clouds to a single characteristic horizontal dimension. This version of the radiative transfer equation accounts for the altitude-dependent cross sections, and altitude and polar angle dependence of cloud size and spacing. The result is a one-dimensional equation that accounts for the three-dimensional cloud geometry under assumed horizontal invariance of the cell material and of the transition probabilities.

The incoming radiation is assumed to be specified and non-stochastic. The ensemble-averaged intensity is assumed to be equivalent to the average intensity. This is considered a low-order model, which assumes that the radiation field and the underlying geometry can be described as a Markovian process.

Model

The stochastic model (Byrne et al. 1996) is composed of two components—a spectral radiative transfer model and a model atmosphere. The spectral model is a band model based on the exponential-sum fitting scheme of Wiscombe and Evans (1977) that calculates the shortwave radiative transfer through a partially cloudy atmosphere. The current version of the stochastic model has 38 bands, which range in wavenumber from 2500 cm^{-1} to 50,000 cm^{-1} in unequally spaced bands. Each band has two possible absorbers, depending on the wavelength. Two of the prime absorbers are water vapor and ozone, although carbon dioxide and molecular oxygen are included as well.

To calculate the radiative transfer in a realistic atmosphere, the model is initialized with profiles of pressure, temperature, moisture, carbon dioxide, and ozone. The profiles are taken from McClatchey's climatological values (McClatchey et al. 1972) for midlatitude summer. The model atmosphere is divided into 32 layers, with a reflective surface, but no surface parameterization. The model is applied to an area approximately 250 km by 250 km. Additionally, information about the cloud field derived from observations is input. This includes cloud base height, cloud top height, cloud water amount, effective radius, and cloud fraction. The characteristic scale of the clouds, both horizontal and vertical, is also specified.

A discrete-ordinate method is used to solve the radiative transfer equation, with an approximate iterative technique. Only isotropic scattering is considered. Detailed information about the characteristic geometry and physical properties of the cloud field is ingested. Droplets have an effective radius dependent on cloud type and the gamma-r distribution used by Stephens (1978). The single-scattering albedo of the droplets and the absorption process are from Smith and Shi (1995).

The model solution is the intensity averaged over an ensemble of cloudy scenes equivalent statistics. The intensity is also averaged over horizontal variations. The result is not specific to a single small area or to only the cloudy portion of an area. The theory provides an accurate solution only for an ensemble average over many scenes with the same probability distributions (Byrne et al. 1996). The output of the stochastic model is the ensemble-averaged radiative components at each atmospheric layer for each band, in addition to pathlength information for clear and cloudy sky.

Data

This study presents a novel method for investigating cloud spatial and physical properties using ground-based observations. The days selected for this analysis were dominated by small, scattered clouds difficult to represent in GCMs. Continuously sampled data from the ARM Program (Stokes and Schwartz 1994) are used to study the physical and geometric characteristics of scattered cumulus and stratocumulus clouds. Information about the cloud field is compiled for a total of 45 hours for three cloud types. The characteristic cloud base height, cloud top height, cloud fraction, cloud liquid water path, and cloud chord lengths are assembled in cloud-size and cloud-spacing histograms. The spatial characteristics are consistent with those obtained by other remote-sensing techniques, and from in situ photographic analysis. In addition, the appropriate solar angle must be supplied to the model. The clouds are generally smaller than 500 m in diameter with a fractional amount of 50% or less.

To isolate the cloud type of interest, hourly meteorological logs were analyzed to identify the occurrence of broken, low-level clouds. The reported cloud types were evaluated against images recorded by the time-lapsed cloud video camera and the whole sky imager to verify the continued presence of the cloud type between the hourly observations.

The Belfort laser ceilometer (BLC) was employed to determine cloud base height. The cloud base heights are binned in 100-m increments, and the number frequency of reported base heights in each height class is shown in Figure 1a. This value differs from the actual number of clouds present because the height of a single cloud may be measured more than once as it passes overhead, and because clouds may be missed by the instrument during the processing cycle. Additionally, the BLC can be used to determine a one-dimensional fraction by calculating the percentage of time that a cloud was detected relative to the entire time sampled. Hourly averages of cloud fraction are compiled from several instruments and compared to the human observer reports of the for each cloud type (Figure 1b). The liquid water path (Figure 1c) is derived from observations made by the microwave radiometer.

The wind speed measured at the ARM site is combined with the cloud base height information to give an indication of the size of the overhead clouds. The multifilter rotating shadowband radiometer (MFRSR) is used to calculate how long the direct normal radiation is blocked by a cloud, then to multiply the time by the wind speed at the height of the cloud. The narrow field-of-view (~8°) traces a path, or chord, from the leading edge to the trailing edge of the cloud. At a characteristic height of 800 m, the aperture radius is 57 m . The data is normalized by the most proximate clear-day signal, to determine a transmission ratio. The transmission ratio threshold is chosen to identify cloudy segments of the signal, with an average threshold of 0.9. The resulting cloud chord lengths are compiled in a population distribution. To better characterize the cloud field, this analysis was performed using six MFRSRs. Two are located at the central facility in the SGP site, and the other four surround the center two. The smallest distance between the peripheral and the central stations is 20 km and the largest is 90 km. A cloud size and spacing analysis was performed for half the days in the Type 1 data set (Figure 1d). This result suggests that averaging a single station over long periods yields similar results as multiple horizontally distributed observations over shorter times. It is, therefore, possible to obtain robust statistics describing the cloud field from point measurements, given enough time.

Results

Comparisons of the stochastic model with a typical two-stream shortwave model are made for one of the Type 1 days analyzed. For the model comparisons, observed information about cloud height and thickness are ignored and both models contain cloud in the second model layer, with a base height of 1.01 km and a thickness of 0.98 km.

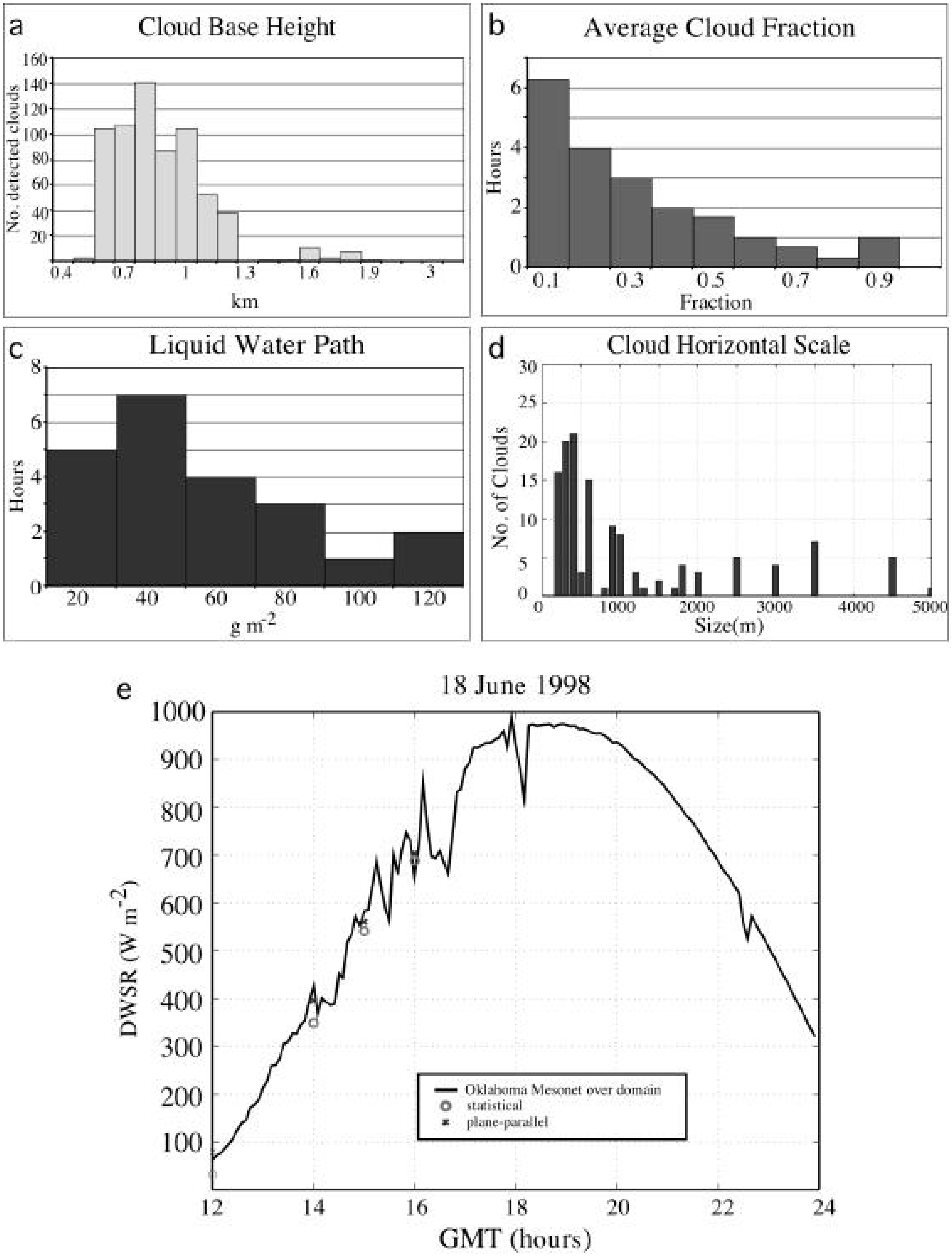

Figure 1. (a) Histogram of cloud base height, (b) cloud fraction, (c) liquid water path, and (d) horizontal cloud scale for five days of fair weather cumulus clouds. (e) Comparison of model results with observations for June 18, 1998.

The downwelling shortwave radiation observed at the surface of the ARM SGP site by the Oklahoma Mesonet (solid line) and calculated by the two models are shown in Figure 1e. The Oklahoma Mesonet (Brock et al. 1995) data have been averaged over all the stations that were under that broken cloud field. Each point of data is an average over 5 minutes of hemispheric broadband downwelling radiation. The circles in Figure 1e indicate the results of the stochastic model and crosses show the results from the plane-parallel model. The difference in the models' simulation of transmission is 32 W m^{-2} on average. In addition, the stochastic model is generally within 29 W m^{-2} of the observed value. The two models disagree most on this day when the cloud fraction is largest. Further investigation into the observational input to both models shows that for this day, the observed cloud base height and cloud thickness were quite close to the predefined model values of 1.01 km and 0.98 km. This finding suggests that both models may be sensitive to information about the thickness of the cloud layer.

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