Stochastic Radiation Transport for Climate Models

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Thesis

Computation can and will, in the near future, predict cloud morphology based upon knowledge of the local intrinsic variables such as heating rate and humidity profiles. Among the desired variables are the size distribution, in space and optical depth, of the clouds.

The radiative effects depend upon both the amount and the morphology of cloud. Data from the Atmospheric Radiation Measurement (ARM) Program will allow us to parameterize morphology in short run and will lead to adequate predictive theory and models in longer run.

Our approach, therefore, is to use ARM data to determine the statistics of observed cloud fields and to calculate the resulting radiation transport in a statistical manner; that is, we hope to predict the average energy balance from a knowledge of the average statistics. Because radiant energy transfer is a nonlinear function of the medium traversed, this is a nontrivial problem.

Areas of Research

The four general areas of research are described below:

1. **Functional Cloud Cover**. This is our first attempt at a simple correction to common general circulation model (GCM) radiative treatments.
2. **Theory of Stochastic Transfer**. We have shown that the Titov and Pomraning-Levermore solutions to a certain problem in stochastic transfer, though apparently very different, can be reconciled.
3. **Effect on Model Calculations**. We have used the Scripps Single Column Model as a stand-in for a GCM in an investigation of the effect of our first functional correction tables on climate prediction.
4. **Tests of Stochastic Theory**. We have performed some numerical tests of stochastic transfer theory, and have constructed a radiation scene generator that should allow better tests to be performed. This prototype machine does not produce data, but it does demonstrate that a useful experiment could be designed and performed in a similar apparatus.

Functional Cloud Cover

Goal

Our goal is to derive a method of handling the cloud-radiation problem that will improve the accuracy of GCM codes and lead to increased accuracy in the prediction of global climate change. We want a method that is

- simply implemented in existing codes, to increase the chance that it will be actually used, and

- very fast to run, because of the large number of scenes that must be considered in every time step of a GCM.

Technique

Our technique is to apply some new results of stochastic radiation transfer theory to the problem of radiation transport through clouds, for both the scattering-dominated short-wave solar and the absorption-dominated long-wave terrestrial reradiation. We are using the ARM observations for two purposes: 1) to choose a statistical description of the clouds over the ARM site, and 2) to test the results of our model calculations against observations *in situ*. The results will be presented in tabular form, allowing a GCM to replace its calculated cloud cover with one which is functionally equivalent to the real cloud cover for the purposes of radiative energy balance, *given the radiative approximations of the GCM.*

Stochastic Radiative Transfer

The general equation in this one-dimensional geometry for the average radiation intensity at direction cosine μ is

$$\mu\frac{\partial}{\partial z}(p_i I_i) + \sigma_i p_i I_i = \int_{-1}^{1} d\mu'\, \sigma_i^s(\mu,\mu')\, p_i I_i(\mu') + p_i S_i + \frac{p_j \bar{I}_j}{\lambda_j} - \frac{p_i \bar{I}_i}{\lambda_i} \tag{1}$$

where we distinguish two media, cloud and clear sky, and label them by i and j. σ stands for the attenuation coefficient, σ^s for its scattering part, and λ is the scale length for transition from sky to cloud or *vice versa*. The barred I's stand for the conditional probabilities, when making the transition from one medium to the other. This equation is exact as it stands, within the stated approximations, but is incomplete since we do not know how to relate the barred I to the unadorned one.

If we have a Markov distribution of cloud *and no scattering,* then we can use the simple closure, in which case the problem reduces to a simple set of two differential equations in two unknowns and can be solved readily. This is such a strong condition that the answer is of little interest—scattering is always present to some extent, the cloud size distribution is not Markovian, and a simple binary distinction of cloud/clear is unsupportable.

Pomraning has suggested a simple modification of this closure that seems to give much more accurate solutions, in a set of numerical test problems. Supplement Equation (1) by the closure:

$$\mu\frac{\partial}{\partial z}(p_i \bar{I}_i) + \sigma_i p_i \bar{I}_i = \int_{-1}^{0} \sigma_i^s(\mu,\mu')\, p_i \bar{I}_j(\mu')\, d\mu' + \int_{0}^{1} \sigma_i^s(\mu,\mu')\, p_i \bar{I}_i(\mu')\, d\mu' + p_i S_i + \frac{p_j \bar{I}_j}{\lambda_j} - \frac{p_i \bar{I}_i}{\lambda_i} \tag{2}$$

for μ along the direction of I, and with the integral limits reversed otherwise. These two equations give an accurate, but still approximate, average solution to the set of problems, not the solution of the average problem.

Results

Our results, so far, include a computation of sample correction functions based, in the absence of ARM data, on a simple model of cloud morphology that has little to recommend it beyond simplicity. They have been implemented in the SIO Single Column Model and the effect of these changes has been determined and will be presented below. We do not claim accuracy at this stage, but we have demonstrated feasibility of the functional technique. The geometry of the stochastic calculation we use as a first case is shown in Figure 1.

We have taken a semiinfinite layer of thickness L and assumed a uniform randomly distributed population of elliptical clouds with horizontal extent D and vertical height H. Their volume fraction is p. Scatterers (shortwave mockup) and absorbers (longwave) are both modeled. Both diffuse and narrow beam (at solar angles of 0°, 30°, and 60°) have been studied.

Figure 2 shows the transmission expected of a particular set of parameters as calculated using the simple but widely used fractional cloud cover model and the more accurate model given above.

Conclusion

We have found so far that this formulation of the stochastic transfer problem is tractable. We have been able to construct tables using this method, as described below. Our investigation as to number and accuracy of tables required is proceeding.

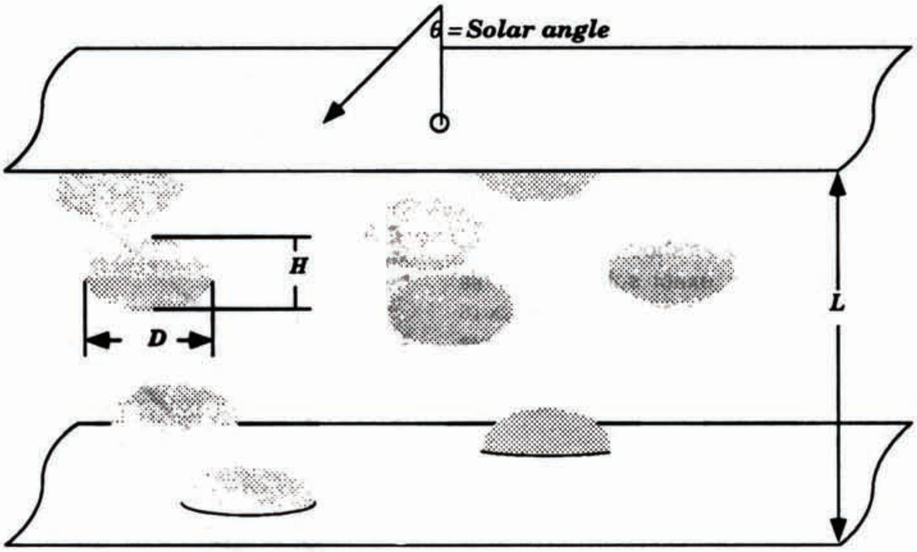

Figure 1. Geometry of model system.

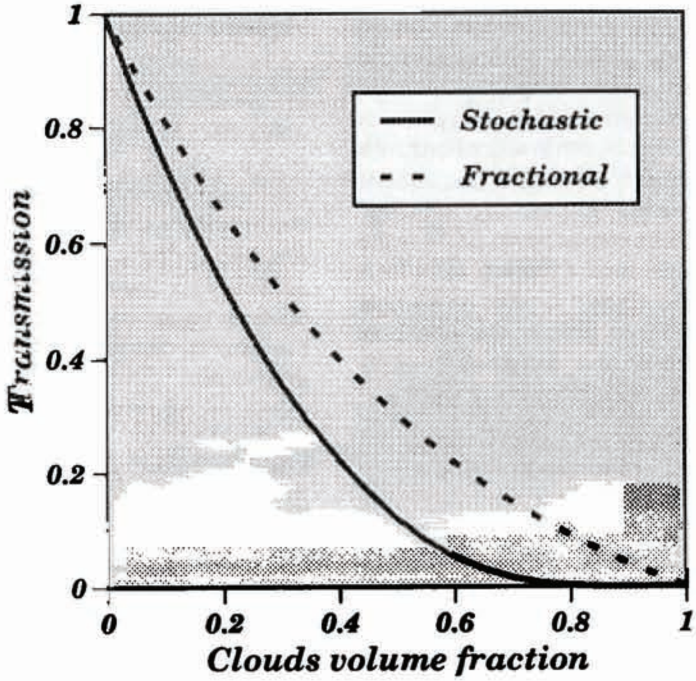

Figure 2. Transmission through absorbing cloud cover.

Stochastic Transfer Theory

Reconciliation: Titov-Pomraning

Titov has solved the problem of a Markovian distribution of clouds in a binary mixture of clear sky and cloud, deriving a set of integral equations. The above formulation, in terms of differential equations, comes from a very different set of considerations, yet both approaches should be correct for this problem, since each is an exact solution for this geometry, assuming that the clouds are pure absorbers and that the clear sky is perfectly transmissive. We have been able to show that, as hoped, the two solutions agree in this case. The differential method we espouse as more generality, however.

Effect on Model Calculations

Sensitivity of Single Column Model (SCM)—Ocean

We wish to estimate the effect of this new stochastic treatment on GCMs. As a simple, relatively controllable stand-in for a GCM we use the Scripps Single Column Model, which has the general physics packages of the standard GCMs in it, but gains simplicity through replacement of the three dimensional fluid dynamics calculation by a one-dimensional column in which horizontal divergences are specified and only the vertical calculations are performed, making it a geometric mean of a radiative-convective model and a full three-dimensional GCM. In the absence of ARM data, we assumed a general form for a functional correction table and made it depend on a single parameter. As a function of this parameter, the functional correction table (there was only one, assumed to apply both to longwave and shortwave) is shown in Figure 3.

Some results of this calculation, for the Indian Ocean at the start of the monsoon season, are shown in Figure 4.

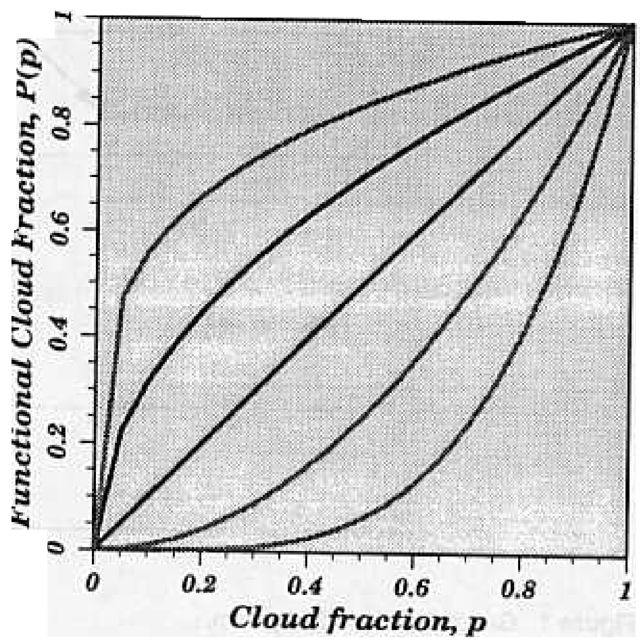

Figure 3. Functional forms used in the study.

Tests of Stochastic Theory

Numerical

We have tested the new closure prescription by running a large number of computer calculations. For a given set of statistical parameters, we generate many problems with input chosen at random from the desired distribution, then solve them numerically. With this technique we can include both scattering and absorbing media, as well as arbitrary mixtures. Computer time constraints limit us to one-dimensional geometries, though. We have solved both rod and slab systems. The results generally indicate increased accuracy for the new closure as far as global quantities such as transmission and absorption are concerned, but the spatial distribution of absorption is not completely understood.

Experimental

In part because the large number of problems we must run on a computer to get a meaningful average of the solution (which effectively restricts us to one-dimensional systems) and in part because of the desire to proceed with the research in the period before actual ARM data is available, we investigated the possibility of building a laboratory-scale machine that could be used to test stochastic transport theories. For a parts cost of under $200 we put together the apparatus shown in Figure 5.

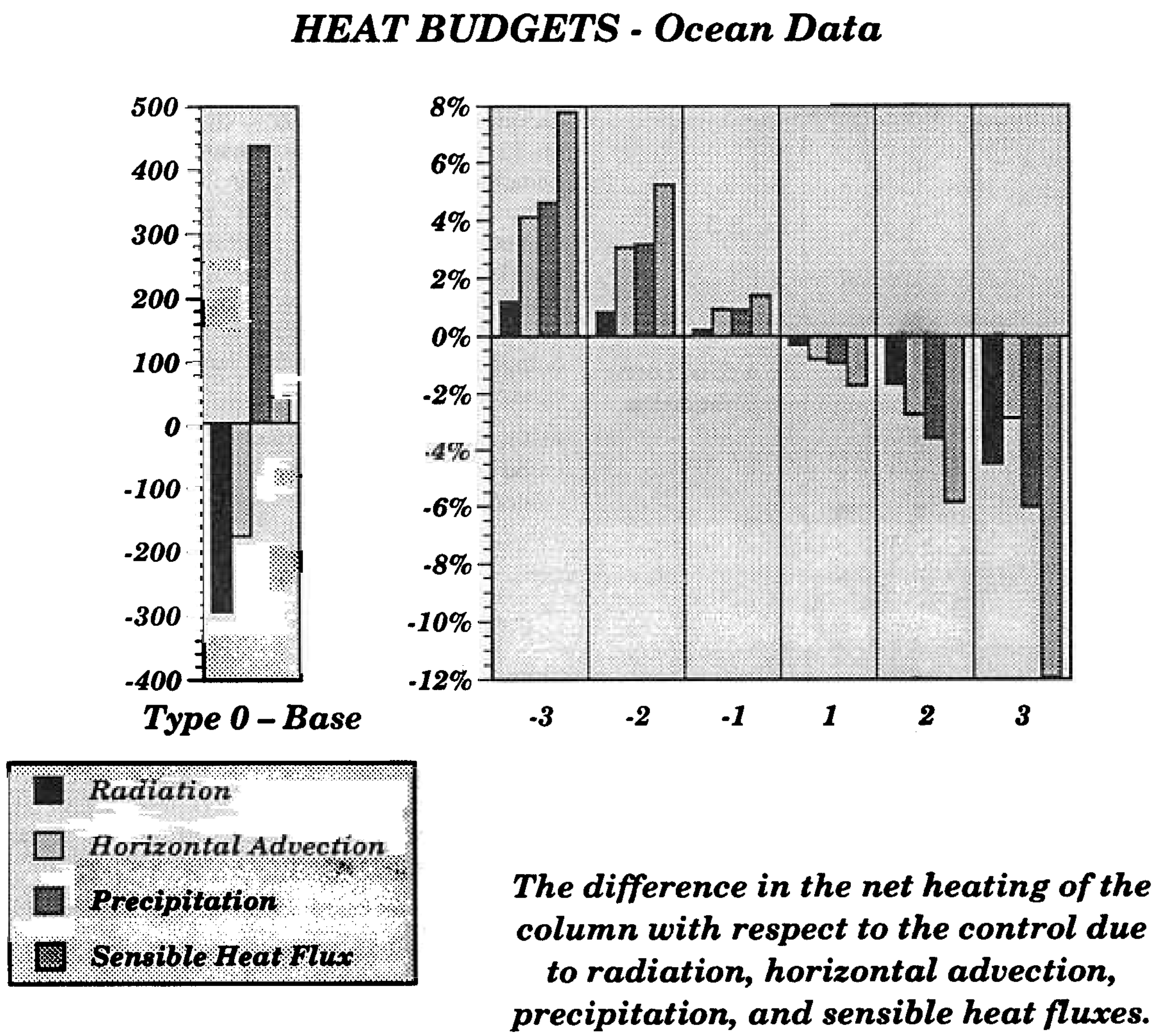

Figure 4. Results: heat budgets over ocean.

This machine is a cylinder lined with shiny foil, containing a controlled number of styrofoam beads. These are very white and very light. They are agitated by a stream of air introduced from below, and are contained by a set of screens at the top and bottom of the experimental volume. A small halogen bulb is at the focus of a (borrowed) telescope mirror, which produces a parallel beam of test radiation. Photodiodes are located at the top, midplane, and bottom. The air flow is regulated by varying the fan speed, and the resulting agitation of the spheres ranges from a slow heave to a completely volume-filling random motion.

The results, shown in Figure 6, indicate that the output of the photodiodes is stable over a period long enough with respect to that required for the radiation transfer problem to be completely redefined. Actually, we observe no significant drift in the optical properties of this simple system for periods exceeding half an hour.

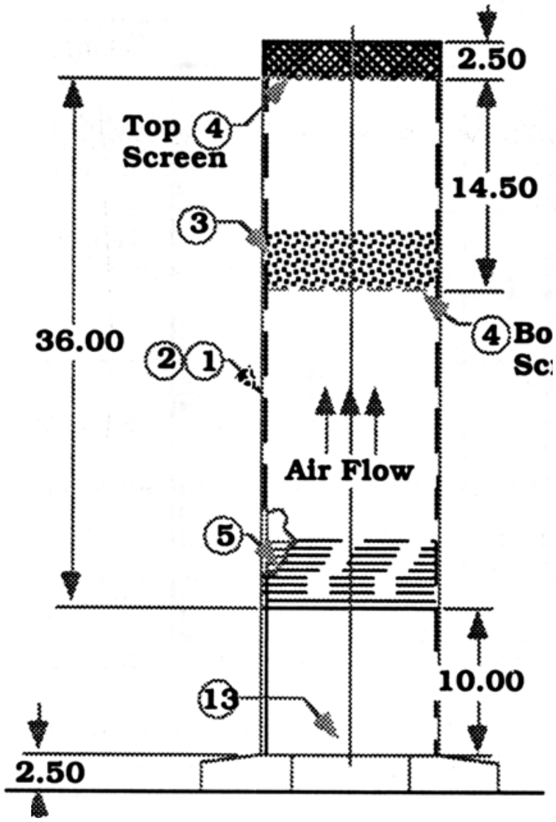

Figure 5. MicroARM machine.

We conclude that this concept is capable of development into a device that could perform useful service in experimental stochastic radiation transfer. The diagnostics on the prototype are inadequate for anything other than demonstrating that the machine works and would have to be supplemented with a better set before useful data could be obtained, but we have shown that the experiment is possible, that the output is steady over many decorrelation times, that the measurements are precise and reproducible, and that the input (air flow, density of spheres) affects output; although this is not documented here, it has been observed in the lab.

Although the styrofoam spheres are not the water droplets found in clouds, the radiation problem they present is related, and this is a more controlled experiment than is easily reproduced elsewhere.

Conclusion

We have made progress in the area of functional cloud cover (correction tables for GCMs), in theoretical stochastic transfer (especially the reconciliation of the Titov and Pomraning approaches to the Markov problem), in the effect of improved cloud-radiation interaction on GCMs through the application of the Scripps code, and to numerical and experimental tests of stochastic theory.

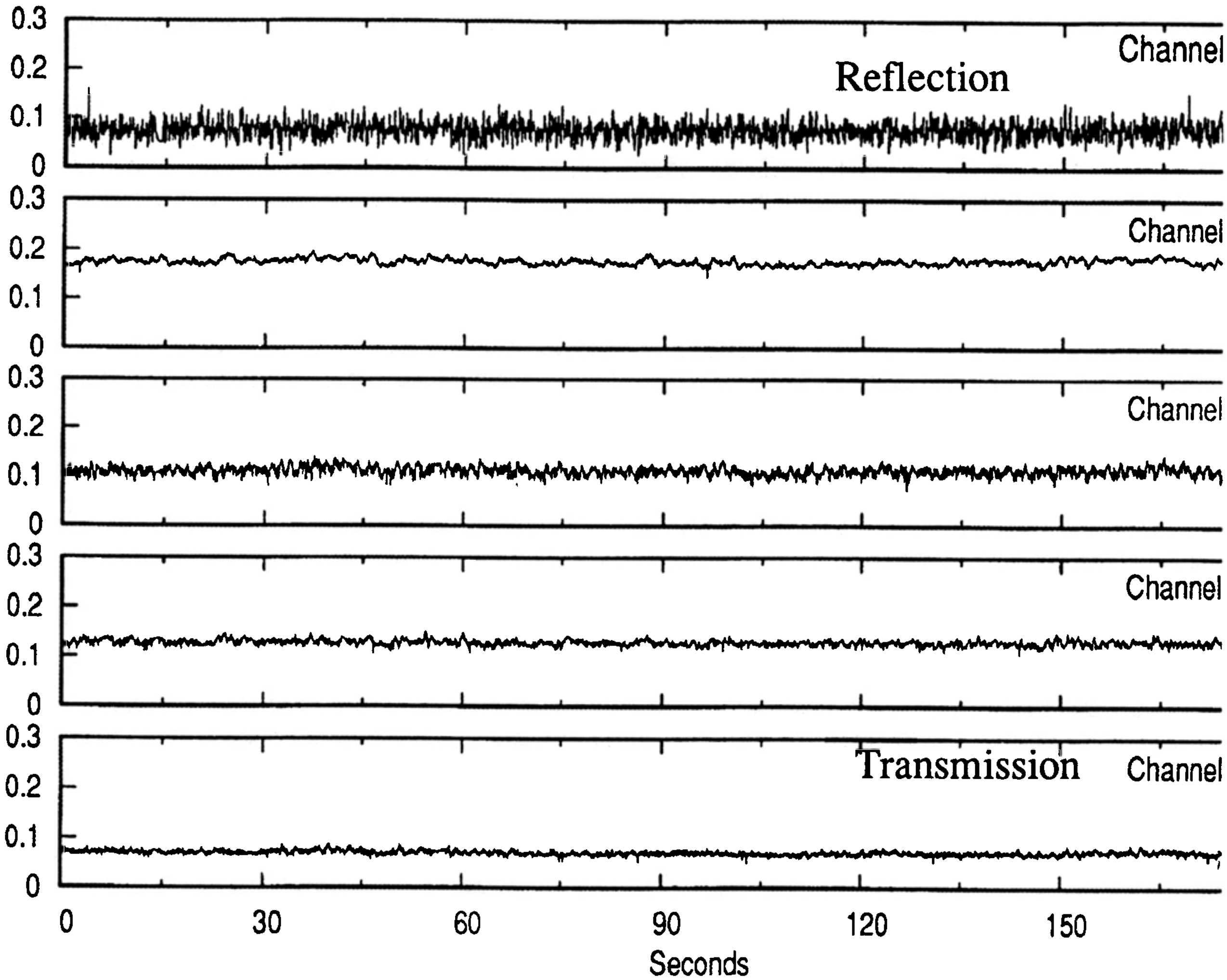

Figure 6. Sample results of radiation experiment.