Colorado State University 3-D Monte Carlo Model

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1. The Origins of the Model

The model we employed for this intercomparison is a modified version of a forward Monte Carlo scheme used for the calculation of high-spectral resolution, domain average shortwave fluxes in three-dimensional scattering atmospheres. The complete model is separated into two parts: the Monte Carlo calculation and an equivalence theorem calculation. The Monte Carlo portion computes domain average fluxes and path length information for a model atmosphere without gaseous absorption. The equivalence theorem portion then uses the fluxes and path length information to incorporate gaseous absorption and produce the final fluxes. Further information about the equivalence theorem method can be found in Irvine (1964), Van de Hulst (1980), and Partain *et al.* (1999).

The original model was constructed to run on the Cray T3E supercomputers located at the Lawrence Berkley National Laboratory (LBNL) and the Geophysical Fluid Dynamics Laboratory (GFDL). The Cray T3E computers are multi-processor machines that enable portions of programs to run in parallel, reducing overall run time. In this application, 1 to 128 processors are employed which introduce photons into an associated grid box on the top of the model atmosphere. Each processor then tracks the photons, one at a time, through the atmosphere until they exit the bottom (unless the surface albedo is non-zero) or top of the atmosphere (boundaries are periodic in the x and y dimensions). Meanwhile, photons are counted as they pass through levels at which fluxes are to be calculated and their corresponding path lengths are stored.

Other details of the Monte Carlo portion of the model include the following. The distribution of photons on the top of the atmosphere is determined with a Halton sequence, whereas random numbers used for scattering purposes are generated with the ran3 subroutine from Numerical Recipes. The model can accommodate single and double Henyey-Greenstein phase functions as well as the input of an external phase function. The model can also accommodate Rayleigh extinction.

2. Changes to the model for I3RC

In order to participate in the Intercomparison of Three-Dimensional Radiation Codes (I3RC), several modifications to the original model were required. First of all, this phase of I3RC does not consider gaseous absorption, so the equivalence theorem routine and all associated path length variables were eliminated. Second, I3RC requires pixel fluxes in addition to domain average fluxes. The ability to track photons crossing flux measurement levels within individual pixels was added. In addition, the capability to calculate nadir, zenith, and oblique radiances were added. The method for doing so followed that in Marshak *et al.* (1995), Appendix A.2:

$$E_j(\Omega^*) = \sum_{k=1}^{N} \omega_o^k P(\Omega_k, \Omega^*) \exp[-\sigma_j \tau^*]$$

where $E_j(\Omega^*)$ is the contribution to the radiance at grid point j exiting the cloud in the direction Ω^*, ω_o is the single-scattering albedo of the cloud, $P(\Omega_k, \Omega^*)$ is the value of the phase function when the photon scatters at an angle between Ω_k and Ω^*, and λ^* is the optical path traversed as the ray is traced out of the cloud in the direction Ω^*. This entailed the creation of code to retrieve the proper phase function value and integrate optical depth from each scattering point in the direction required for each radiance.

Rather than using the Cray T3E systems, the new model is run on a cluster of 9 workstations at Colorado State University. Each workstation possesses a Pentium II 450 MHz processor. The functional difference between this cluster and the T3E systems is in the decreased speed of communication between processors. However, this is not an issue for the Monte Carlo model because processor "cross-talk" is kept at a minimum. On the other hand, the equivalence theorem routine in the original model requires much more information exchange between processors.

Perhaps the largest source of uncertainty is the use of a fixed number of photons for each case rather than tracking error and terminating an experiment when the error levels are below a specified amount. For domain average fluxes, errors are generally smaller than those for pixel fluxes, especially when large numbers of pixels are used. Therefore, the original model did not have error calculation built in. Due to time constraints, error calculation routines were not added to the new model.

3. Experiments

Three different cloud fields were used in this phase of I3RC including a two-dimensional step cloud, a two-dimensional cloud retrieved from radar observations (MMCR), and a three-dimensional cloud retrieved from Landsat observations.

A. A. step cloud

This cloud field consists of 32 cloud cells in the x-direction and 1 cell in the z-direction. The first 16 cells have an optical depth of 2 and the last 16 cells have an optical depth of 18. For this field 9,000,000 photons were simulated resulting in an average of 281,250 photons injected into each cell. Resulting domain average albedo, transmittance and nadir reflectivity values along with associated standard deviations agree well with the mean of the results from the other participants in this intercomparison. Although this is not the same as comparing absolute accuracy against a single benchmark, it does provide confidence that this model is very nearly getting the same answer as most of the other models in this study. The results for the step cloud and other cases can be seen on the I3RC website (http://i3rc.gsfc.nasa.gov).

B. B. MMCR

This cloud field consists of 640 cloud cells in the x-direction and 54 cells in the z-direction. Here, 27,000,000 photons were simulated resulting in 42,188 photons being introduced into each cell at the top of the atmosphere. We would expect errors to increase for pixel-level quantities over those seen for the step cloud case. As suspected, domain averaged results for reflectance, transmittance and absorptance agree fairly well with the other Monte Carlo models. The pixel-level comparisons, however, show more noise than they did for the step cloud, although agreement is still very good with the other models.

C. C. Landsat

The Landsat cloud field consists of 128 cells in the x- and y-directions. Cloud top heights were provided for the third dimension. For use in this model, the cloud top heights were binned into a 100-meter vertical grid resulting in 24 cells in the z-direction. 90,000,000 photons were used, translating to 5,493 photons per cell at the top of the atmosphere. Errors for pixel-level quantities using this small number of photons per pixel were expected to be larger than for the MMCR case. As suspected, the 2-D images of the radiative quantities are fairly noisy compared to Monte Carlo codes that used more photons and as compared to the analytic solution methods. However, the noise is certainly not unacceptable. The level of agreement for the domain averaged quantities is very good as it was for the previous cases.

4. Future Considerations

The modified Monte Carlo model used for this intercomparison is not ideally suited for computing pixel fluxes. No attempts to accelerate the scheme with analytical techniques have been made. However, this intercomparison has been useful to test this model's ability to calculate domain average quantities and show its capabilities concerning pixel-level fluxes. The basic schemes involving scattering and photon distance calculations are no different than those in the original model. Up to this point, only plane-parallel atmosphere results had been verified. We are very pleased with the overall performance of this code in comparison with the other participants.

The degree of involvement for this model in phase 2 will be determined at a future date, depending upon the experiments chosen. At the very least, this model along with the equivalence theorem scheme can contribute domain average broadband results. Broadband results for pixel quantities, aside from the large error in pixel fluxes, may not be possible as a result of the large amount of path length information that is required. Options for experiments in phase 2 might include complex layered clouds with different phase function properties (ice and water clouds in the same atmosphere) and Rayleigh scattering in addition to gaseous absorption.

5. References

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