An Intercomparison of Solar Radiative Transfer Algorithms

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Introduction

The Intercomparison of Radiation Codes in Climate Models (ICRCCM) was a successful radiative transfer model intercomparison program that was performed under the auspices of the World Climate Research Programme (WCRP) beginning in 1984. The objectives of the ICRCCM (Ellingson and Fouquart 1991) are to

- develop a better understanding of the differences in model approaches.
- understand how these differences affect model sensitivity.
- evaluate the effects of simplifying assumptions.
- evaluate the effects of using different sources of spectral line data.
- evaluate the ability of the models to simulate the disposition of fluxes for real atmosphere.

Though ICRCCM addressed longwave and shortwave radiative transfer for a number of model atmospheres, all test cases were restricted to plane-parallel and homogeneous (PPH) conditions. Furthermore, for cloudy atmospheres, benchmark line-by-line (LBL) calculations have not been available for comparison to other model results. To remedy these deficiencies and add new items to the above list of objectives, ICRCCM is being resurrected under the WCRP radiation panel. ICRCCM II will focus on cloudy-sky transfer beginning with the solar portion of the spectrum. Special attention will be given to assessing how well general circulation model (GCM) codes parameterize and handle unresolved cloud fluctuations. Model intercomparisons will also be performed for different methods of solving for three-dimensional (3-D) transport to determine the accuracy of each. This paper describes part of the framework of the intercomparison and a new LBL 3-D Monte Carlo algorithm that will be used as the benchmark for the program.

Goals of the Intercomparison

GCM radiative transfer schemes are generally restricted to plane-parallel and homogeneous (PPH) atmospheres primarily because sophisticated codes that accommodate more complex atmospheres are computationally expensive, and the information needed to drive these codes is not available. Furthermore, the scale of the GCM model atmosphere is large with horizontal domain sizes often exceeding 200 km. Usually, some degree of cloud heterogeneity is introduced through parameterizations. Even with these corrections, inadequate treatment (or neglect) of horizontal and vertical cloud structure introduces substantial biases in simulated energy and hydrologic budgets. Thus, the primary goal of ICRCCM II is to determine the accuracy of these one-dimensional (1-D) models in terms of radiative fluxes and heating rates. More specifically, results will be analyzed to determine the effects of

- assumptions about overlap of fractional cloud made for 1-D algorithms
- treatment of fractional cloud
- assumptions employed to define atmospheric optical properties
- horizontal variability of cloud extinction.

Several model atmospheres will be selected from the Global Energy and Water Experiment (GEWEX) cloud system study (CSS) as case studies for the intercomparison. Though all of the cases have not yet been chosen, they will include

- conservative-scattering test cases
- PPH test clouds
- a stratocumulus cloud field
- a shallow cumulus cloud field
- a tropical convective complex.

Unlike the original ICRCCM, benchmark results will be available for all cases. The following section describes the theory behind the benchmark model.

Benchmark: LBL 3-D Monte Carlo Algorithm

Because the Monte Carlo method of radiative transfer solution uses a straightforward photon-tracing routine, it is ideal for simulating accurate radiative transfer through heterogeneous cloud fields. However, because this method traces the entire life span of each photon it can be time consuming. The computational cost has long prohibited this method from being used for high-resolution spectral studies. For benchmark broadband calculations, the spectral flux resolution is very high over a wide spectral region. This sort of calculation is very time consuming for conventional PPH models and impossible for conventional Monte Carlo schemes [unless spectral information is to be compromised for improved efficiency (see Barker et al. 1998)].

The approach used here employs modifications to Irvine's (1964) equivalence theorem. A more thorough discussion can be found in Partain et al. (1998). Because gaseous, cloud, and surface absorption do not affect a photon's trajectory, all three can be accounted for at any spectral resolution after the simulation as long as the spectral scattering properties of the atmosphere are resolved by the Monte Carlo model. The attenuation of radiation due to absorption is calculated with photon path length and scattering probability density functions (pdf). If the flux F_o is returned from a conservative-scattering Monte Carlo run, then the flux including only gaseous absorption F_g can be calculated with

$$F_g = F_o \int_0^\infty p(l) e^{-k_g l} dl$$

assuming the pdf of photon geometric path length p(l) is also returned from the model. Here, k_g is gaseous absorption coefficient. Any k_g can be used to calculate spectral flux in a wavelength interval for which F_o and p(l) are constant. To account for vertical heterogeneity of k_g, the mean k_g for each path length is used. This is calculated by returning a path length/layer pdf p(l|n) in addition to p(l). The new form of the above equation is

$$F_g = F_o \int_0^\infty p(l) e^{-l \sum_{n=0}^{N} p(l|n) k_g(n)} dl$$

where N is number of layers.

Like gaseous absorption, cloud and surface absorption are accommodated using the scattering pdfs p(s) and p(r), where s and r are the cloud and surface-scattering order, respectively. Because s and r are discrete events, the pdfs are summed rather than integrated. Thus, the flux including only cloud absorption F_c is

$$F_c = F_o \sum_{s=0}^{\infty} p(s) \omega_o^s$$

where ω_o is droplet single-scattering albedo. The flux including only surface absorption is

$$F_{surf} = F_o \sum_{r=0}^{\infty} p(r) \alpha^r$$

where α is surface albedo.

Because p(l), p(s), and p(r) are not independent of one another, the flux F for all absorbers must be calculated with one pdf that includes all events, p(l,s,r):

$$F = F_o \int_0^\infty \left[\sum_{s=0}^{\infty} \left(\sum_{r=0}^{\infty} p(l,s,r) \alpha^r \omega_o^s e^{-l \sum_{n=0}^{N} p(l|n) k_g(n)} \right) \right] dl$$

For the intercomparison, extremely high resolution in cloud and surface absorption will most likely not be necessary. Wavelength intervals will be chosen that are small enough to resolve the variability in these parameters. However, because gaseous absorption is extremely variable even within small intervals, the equation for the modified equivalence theorem including only gaseous absorption will most likely be used by itself.

Benchmark: Domain-Averaged Fluxes

Benchmark fluxes will be obtained by applying the LBL 3-D Monte Carlo algorithm directly to the 3-D cloud domains. The 1-D GCM codes, however, will operate on degenerate versions of the 3-D cloud domains. That is, profiles of cloud fraction, cloud water paths, and water vapor will be provided to each 1-D code (Barker et al. 1999). If more information is required, it will be provided. In order to focus on how 1-D models treat unresolved cloud fluctuations, plans are to use simple descriptions of cloud microphysics (e.g., fixed effective radii).

Sample Results

This experiment presents differences that might result when the 3-D benchmark model is compared to a 1-D model that uses one of several approximations to account for cloud heterogeneity. These approximations include the following:

- Independent Column Approximation (ICA) - horizontal grid spacing is infinite
- Ideal PPH - same as "ICA" except optical properties of cloudy layers are set to layer averages
- Maximal - same as "ideal PPH" except clouds are repositioned to yield maximal overlapping clouds in contiguous cloudy layers
- Random - same as "ideal PPH" except clouds are repositioned at random across the layer. For all cases, the total cloud mass and cloud fraction are preserved for each layer.

To test each approximation, the four assumptions are applied to a 3-D cloud field (Grabowski et al. 1998). This cloud field, shown in Figure 1, consists of clusters of organized, non-squall tropical convection forced by large-scale wind, temperature, and moisture fields observed during GATE-III. The domain size is 400 km by 400 km by 20 km. The top panel of Figure 2 shows domain-averaged profiles of cloud optical depth τ and cloud fraction as a function of height for the cloud field in which only the liquid phase is present. The bottom panel shows the cumulative cloud fraction for the actual field and the maximal and random approximations.

An example of the spectral solar flux that is calculated by the benchmark model is shown in Figure 3. The bottom two

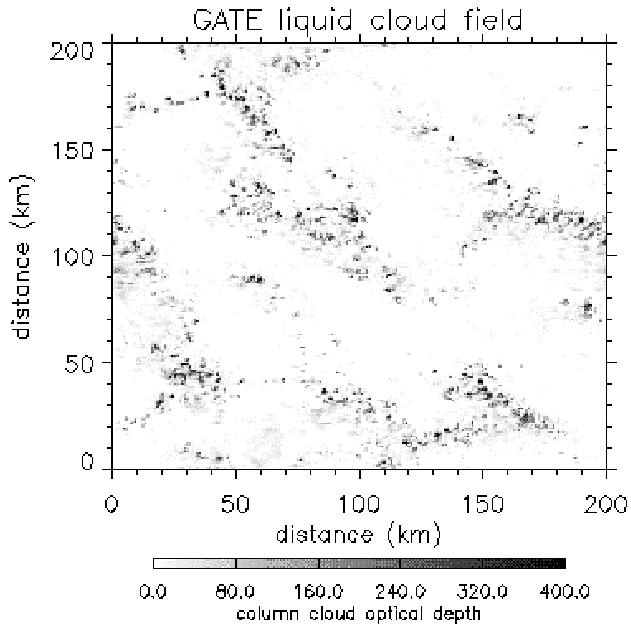

Figure 1. GATE model simulated liquid cloud field (Grabowski et al. 1998).

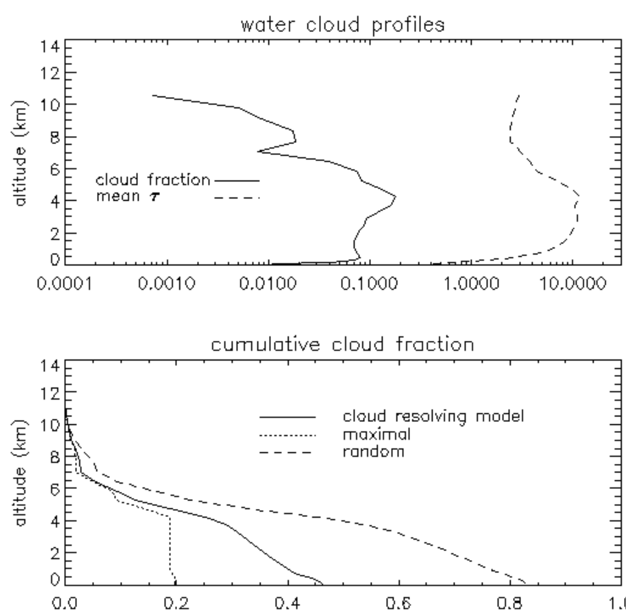

Figure 2. GATE liquid cloud field optical depth τ and cloud fraction as a function of altitude (top panel). Cumulative cloud fraction from the top of the model domain for the field shown in Figure 1 as well as for the maximal and random overlap assumptions (bottom panel).

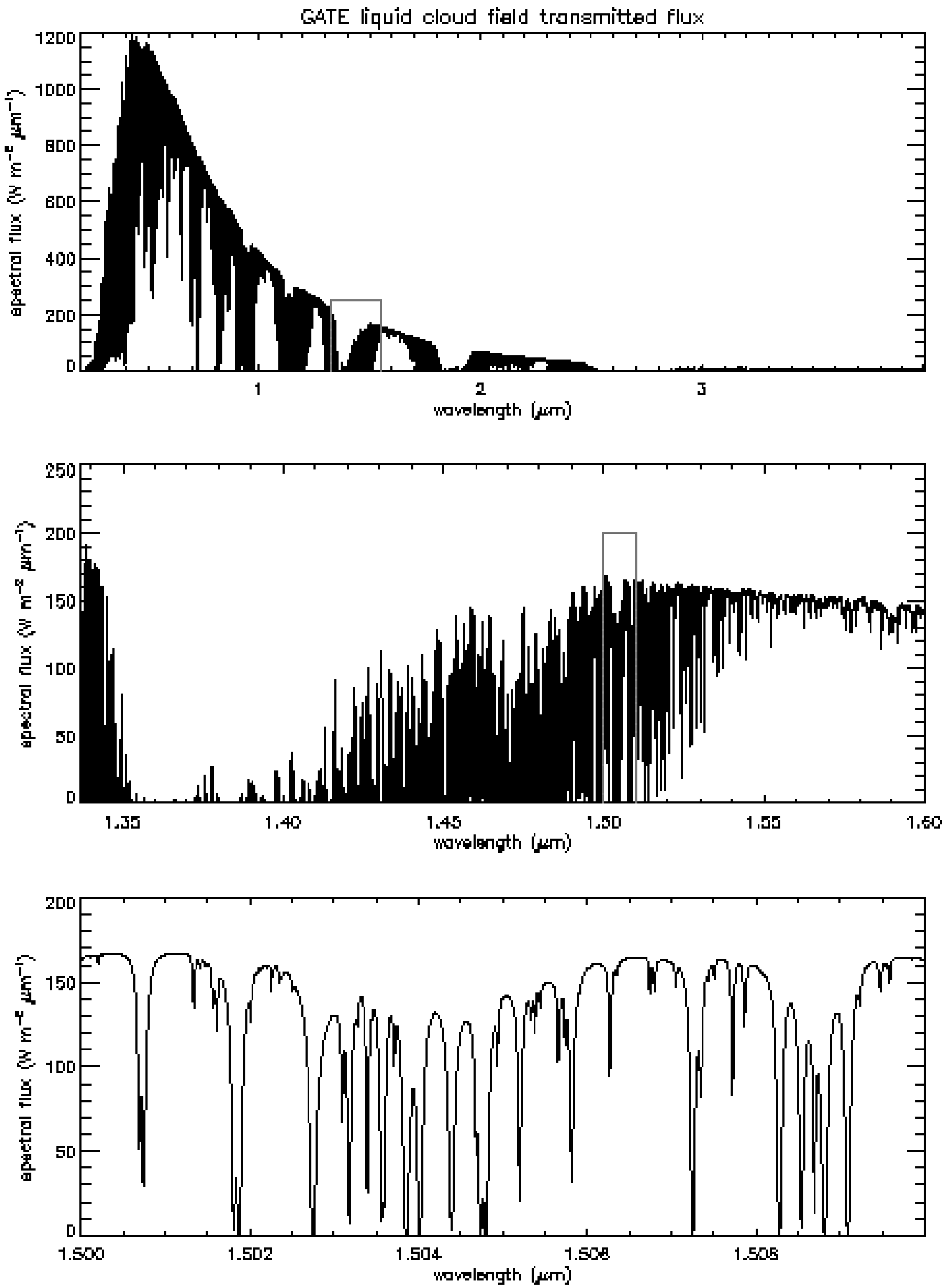

Figure 3. Benchmark LBL Monte Carlo calculation of transmitted spectral flux at the surface below the GATE cloud field (top panel). The lower two panels show enlargements of a portion of the full spectrum.

panels represent subsequent enlargements of the spectrum in the top panel. Only water vapor absorption was included in the model atmosphere. Water vapor absorption lines and the complex nature of the top of atmosphere (TOA) incoming solar spectral flux are responsible for the variability seen in this figure. The spectral flux shown is integrated to provide the broadband flux, which is then compared to that returned from the simplified atmospheres.

Figure 4 shows differences in broadband flux between each approximation and the benchmark calculation as a function of solar zenith angle. As seen, errors can be large when the 3-D atmosphere is parameterized for inclusion in simpler radiative transfer schemes. These errors reach 200 W m^{-2}.

Summary

This paper described the framework for ICRCCM II; a model intercomparison program that will investigate differences in broadband fluxes and heating rates for 3-D and 1-D radiative transfer models. Of particular interest to the climate modeling community will be the biases and ranges that cloud overlap parameterizations cause in conjunction with neglect of horizontal variability.

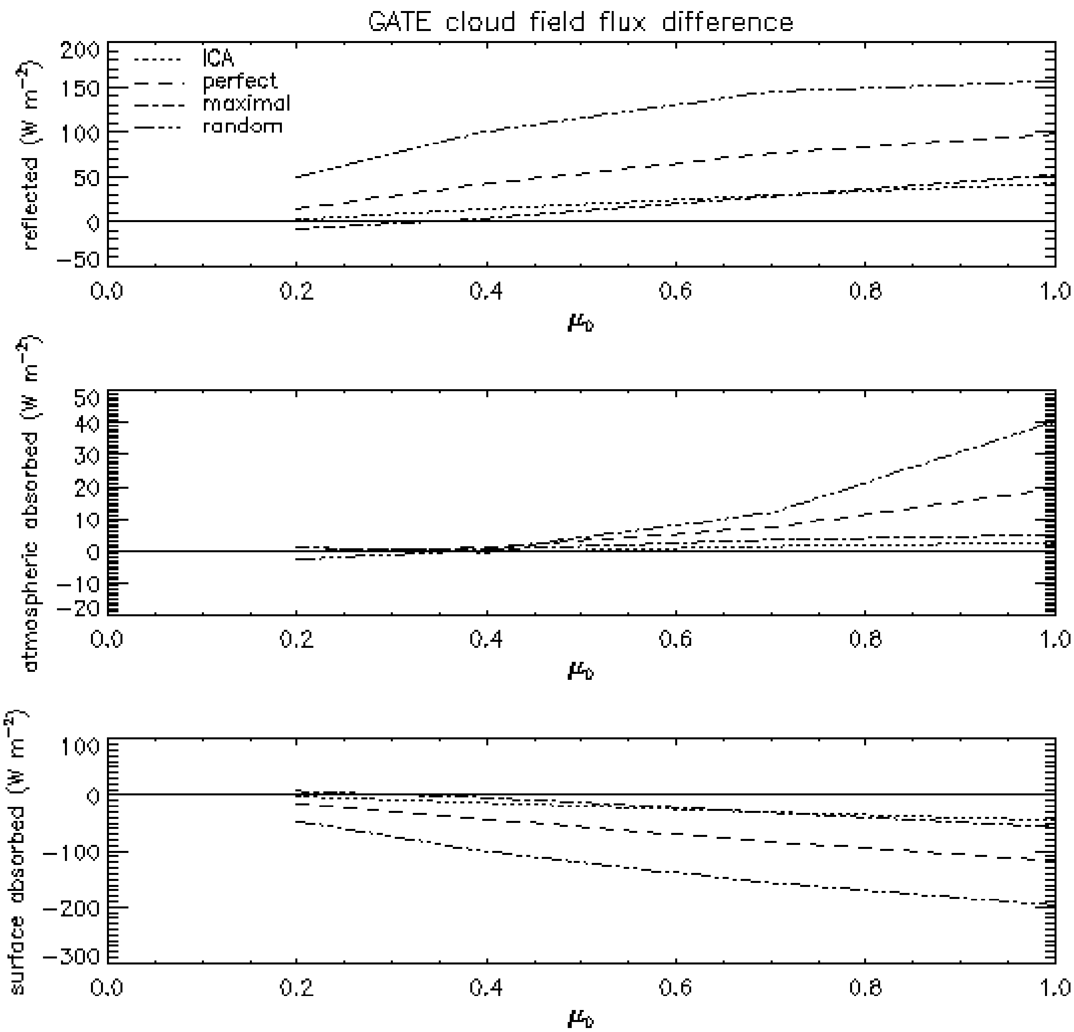

Figure 4. Broadband flux differences between various cloud overlap assumptions and the benchmark calculation for reflected, atmospheric absorbed, and surface absorbed flux.

A LBL Monte Carlo algorithm has been developed to provide benchmark calculations. Modifications to the equivalence theorem of Irvine (1964) make LBL simulations through heterogeneous cloudy atmospheres possible. An experiment was performed to provide a sample of the types of results expected when results from 1-D radiative transfer models are compared to the 3-D benchmarks. This experiment showed that very large differences may be expected with some cloud overlap assumptions and neglect of horizontal variability.

For the intercomparison, several cloudy model atmospheres will be chosen and provided to interested participants. ICRCCM protocols for pooling results and analysis will be followed. Like the original ICRCCM, this study should provide insight into causes of model differences and the accuracy of different methods of solution and parameterization.

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