Radiative Transfer Model Development in Support of the Atmospheric Radiation Measurement (ARM) Program

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Introduction

The availability of a rapid highly accurate multiple scattering radiative transfer model is essential to meet the objectives of the Atmospheric Radiation Measurement (ARM) Program. The model must be capable of computing radiance at spectral intervals consistent with the monochromatic spectral variation of the atmospheric molecular absorption. The resolution of the spectrometers to be deployed at the ARM sites, 0.1 cm^{-1} and less, will provide an important assessment of our capability to perform radiative transfer calculations in the multiply scattered environment. A second important application for the high-accuracy high-resolution model is to provide parameterizations and validations for the faster low-resolution models required for general circulation models (GCMs). The computational cost of performing multiple scattering calculations at monochromatic resolution over broad spectral regions is extremely high. The major focus of our research effort has been directed to the development of an accelerated multiple scattering model for the longwave spectral region.

CHARTS - Code for High Resolution Accelerated Radiative Transfer with Scattering

Lead Investigator: J. L. Moncet

The design of the multiple scattering model has focused on the requirements for ARM, i.e., the computation of multiply scattered spectral radiances for a specified altitude and viewing angle with a computational accuracy of better than 0.1%. The code has been optimized for the computation of radiative transfer results at specific altitudes, e.g., the surface, aircraft altitudes, or space. The code is not optimized for the computation of atmospheric cooling rate profiles at high spectral resolution. Cooling rate profiles can best be obtained by faster models which do not retain the high-resolution spectral information.

Following a thorough consideration of multiple scattering methods in the context of line-by-line spectral calculations, the doubling-adding method has been selected. The method is fast, accurate, and numerically stable. The doubling-adding method is very general; may be readily extended to include polarization and the treatment of multiple scattering in anisotropic media, e.g., cirrus clouds; and involves only elementary matrix/vector operations facilitating accelerated computation. In the CHARTS model, double gauss quadrature (Sykes 1951; Stamnes and Swanson 1981) has been used. The number of streams is variable, limited only by computer memory constraints. In the present model, the number of streams has been varied from 2 to 32. The model uses delta-M scaling (Wiscombe 1977) and the diamond initialization with $\Delta t \sim 10^{-3}$ (see, e.g., Wiscombe 1976). A stratified, horizontally homogeneous, plane parallel atmosphere is assumed. The Planck function is taken to vary linearly with optical depth within an otherwise vertically homogeneous layer.

In general the observing angle, including both zenith and nadir viewing angles, will not be included among the quadrature angles used in the multiple scattering calculation. It has been generally recognized, e.g., Stamnes (1982), that interpolation procedures are not adequate to obtain the radiance to the required accuracy at specified but arbitrary viewing angles. To address this situation, the reflection/transmittance matrices and the emission vector have been augmented by an additional angle, the viewing angle. With an appropriate definition of the relevant matrices and emission vector, the implementation of the interaction principle for adding provides the radiance at the specified angle without including the augmented component in the angular summations.

The accelerated performance of the model arises from two main sources: 1) the application of a look-up table for the multiple scattering matrices as a function of molecular optical depth, and 2) the calculation of the components for the required matrix operations with the spectral loop taken as inner. The model assumes that the phase function and the Planck function may be taken as having a linear variation over 2400 spectral points. The separation between spectral points is taken to be 1/4 of the halfwidth of a typical spectral line for a layer at the tropopause. This corresponds to a sampling interval of 0.002 cm⁻¹ with a span of 4.8 cm⁻¹ for a panel of 2400 points. Using the doubling method, reflection/transmittance matrices and emission vectors are constructed for a range of optical depths appropriate to the molecular optical depths in the panel at logarithmic intervals of 0.1 (base 2). The multiple scattered results are then obtained at spectral value υ by interpolating the reflection/transmission matrices and the emission vector using the molecular optical depth associated with υ. In the current approach, on the order of 100 doublings are required over a panel rather than the 2400 required with a direct approach, resulting in a computational savings of 24.

The second important feature involves performing the computations with the spectral loop taken as the innermost loop, namely over the 2400 spectral points. This has the advantage that the computational gain attainable with vectorization will be realized independent of the size of the matrices, i.e., the number of streams being used.

Finally, for treating the atmospheric problem, a strategy has been developed that provides flexibility and further acceleration for the computations of multiply scattered radiance at an arbitrary atmospheric altitude. For the layers below the specified altitude, the adding algorithm is applied starting at the surface and proceeding to the specified altitude. This method results in the development of the reflectance matrix and emission vector for a single layer from the surface to the specified altitude. For the layers above the specified altitude, the computation is performed from the top scattering layer to the specified altitude, obtaining the reflectance/transmittance matrices and the downward emission vector for an effective scattering layer above the specified level. The scattered radiance at the given altitude is obtained by appropriately combining these quantities in conjunction with application of the spectral radiances at the upper scattering boundary.

In Figure 1, we indicate results associated with the preliminary version of the operational code. The test case con-
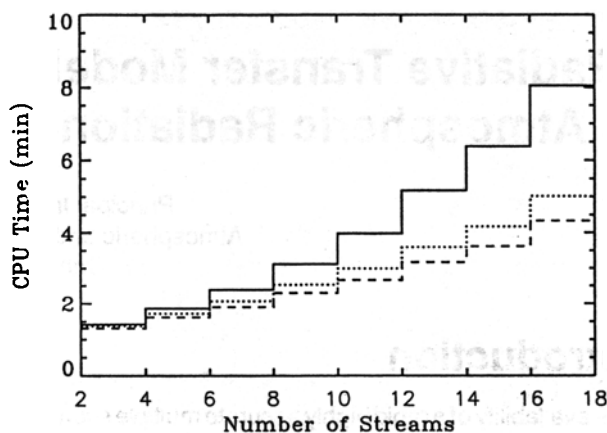
Figure 1. Timing Results for the CHARTS Multiple Scattering Model on a CRAY-YMP as a Function of the Number of Streams. The dashed line represents the time for the table generation; the difference between the dotted and dashed line represents the time for the interpolation; and the difference between the solid and dashed line represents the time for adding. The case is for four scattering layers at 12 km with 1 x 10⁶ spectral points per layer.

sists of four 1-km-thick cloud layers with spectral sampling appropriate to an altitude of 12 km. The spectral region is from 600 cm⁻¹ to 2600 cm⁻¹. Each layer has 1 x 10⁶ spectral points for which the reflectance/transmittance matrices are required. The times are for a four-processor CRAY-YMP in which no parallelism has been implemented. It is anticipated that an additional acceleration of a factor of four will be achieved in the table generation time. This gain may be offset somewhat by the implementation of a scheme that assumes the scattering properties vary linearly across a panel, in contrast to being taken as a constant.

LBLRTM: Vectorized Line-by-Line Model

Lead Investigators: R. D. Worsham, M. J. Iacono

An important aspect of high-accuracy high-resolution radiative transfer is the calculation of spectral optical depths. After consideration of a number of line-by-line codes, FASCODE, developed and supported by the Phillips Laboratory/Geophysics Directorate, was selected as the

line-by-line model best suited to the requirements for accelerated calculation. For our purposes, the model has three main virtues: 1) the model has been extensively validated; 2) the computation of the spectral optical depths by layer is well suited to our implementation of the doubling-adding method; and 3) the code lends itself to vectorization. LBLRTM is derivative of FASCODE in which the radiative transfer modules have been rewritten, and computationally intensive aspects of the code have been vectorized. This model includes the algorithms for the computation of fluxes and cooling/heating rates developed under a parallel DOE-supported effort. An example of the calculation of spectral cooling rates for water vapor is provided in Figure 2. This result is for the mid-latitude summer atmosphere and is consistent with the specifications for the Intercomparison of Radiation Codes in Climate Models (ICRCCM) line-by-line computations. Two important conclusions with respect to the ARM program result from these calculations: 1) a strong correlation is demonstrated between the regions of strong absorption and the altitudes of strong cooling, and 2) the spectral region at 400 cm^{-1} is of significance to the cooling by water vapor in the upper tropopause. The strong cooling in this spectral region is due to the combination of the peak of the

Planck function at ~800 cm^{-1} and the peak of the water vapor absorption at ~200 cm^{-1}.

The computational time for this calculation with 66 layers from 0-3000 cm^{-1} with four spectral points per halfwidth is less than ten minutes on the CRAY-YMP. The time for the calculation of the optical depths is four minutes, and the time for the radiance calculation is two minutes per angle. Three angles have been used for these calculations.

X-Window User Interface for LBLRTM

Lead Investigator: A. Bianco

To facilitate the use of LBLRTM for line-by-line calculations associated with the ARM program, an X-window user interface has been developed. The interface uses a template file and provides for modification and extension of the file for subsequent execution with LBLRTM. The interface provides the user the option to select most LBLRTM functions and includes appropriate interlocks. At this stage, options for creating user-defined atmospheres have not been implemented. This option essentially requires an
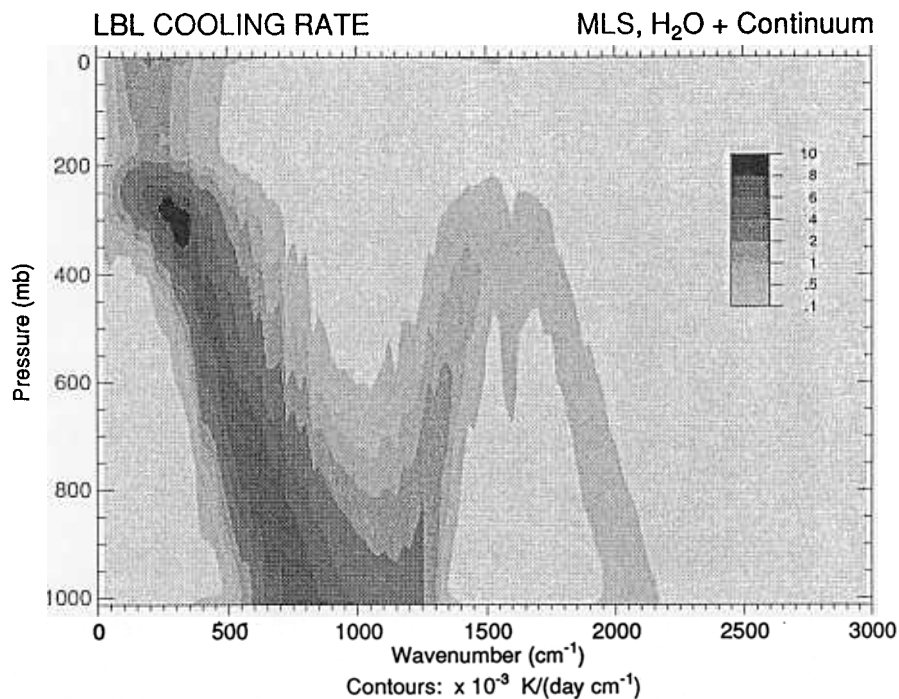

Figure 2. Atmospheric Spectral Cooling Rate Profiles for Water Vapor. The calculations were performed with LBLRTM.

editing or spread sheet function, which cannot be readily developed with the available implementation tools. These functions can be implemented through the use of standard editors. The code is written in C and is run as an OPEN window or X-window application.

Model Availability

The models described here have been provided to Pacific Northwest Laboratory for evaluation and use in simulations of ARM measurements. A mechanism for making these codes available to the ARM Science Team and to the greater ARM community for evaluation and application to atmospheric problems is currently being discussed. LBLRTM and the X-Window interface have also been made available to the Phillips Laboratory/Geophysics Directorate for evaluation and coordination purposes.

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