Moderate Spectral Resolution Radiative Transfer Modeling Based on Modified Correlated-k Method

S. Yang, P. J. Ricchiazzi, and C. Gautier
University of California, Santa Barbara
Santa Barbara, California

Introduction

A new set of high spectral resolution sensors to monitor the variations of cloud and atmospheric properties have been developed and are starting to be deployed either in space or on the ground. The development of improved retrieval algorithms and the analysis of these new data sets require rapid radiative transfer models that have commensurate spectral resolution. Although a number of radiative transfer models are available, user-friendly, accurate, high resolution spectral models that can be used to develop atmospheric, cloud and aerosol retrieval methodologies are missing. This paper describes SBDART-MOD, a new radiative transfer model covering from the visible to the infrared part of the spectrum that could serve as an alternative intermediary standard to the line-by-line models when repeated sensitivity and validation computations are necessary.

The new model is based on the Santa Barbara discrete ordinate radiative transfer (DISORT) Atmospheric Radiative Transfer computer program, or SBDART (Ricchiazzi et al. 1998) to compute shortwave and near-infrared radiation at low spectral resolution. Despite its flexibility, SBDART is not appropriate to use with instruments that have a spectral resolution of 10 nm or better, if filter response functions are to be accounted for properly.

SBDART is user-friendly and allows the user to access a set of physical models describing absorption, emission, and scattering in the earth's atmosphere. For gaseous absorption, it is based on band models from the LOWTRAN 6 computer program (Kneizys et al. 1983) and therefore has the 20 cm^{-1} resolution of that model. For scattering, it is based on the DISORT computer program (Stamnes et al. 1988).

A New Approach to High Resolution Transmission Computations

One approach to the computations of gaseous absorption and thermal emission in the atmosphere is based on monochromatic line-by-line computations. This approach uses a comprehensive line parameter data base, but the computation costs make it feasible only for limited applications. Another less costly approach, the one we have adopted here, employs a drastically different approach, based on the correlated k-distribution and a condensed version of the line data base.

The principal issue with line-by-line computations is the extreme variations of the gaseous absorption coefficients with wavenumber. The correlated k-distribution method (Goody et al. 1989; Lacis and Oinas 1991) avoids the redundant computations of line-by-line models by taking advantage of the fact that the transmission within a band of small spectral width is independent of the spectral sampling order. Re-ordering the quadrature in order of increasing absorption coefficient within the given spectral interval, produces a relatively smooth, monotonically increasing function, which requires many fewer quadrature points to obtain good numerical accuracy. It is on this aspect of the correlated-k method that we capitalize.

Central to our new approach are key components of the Line-by-Line Radiative Transfer Model (LBLRTM) computer program (Clough et al. 1981) that computes atmospheric spectral transmittance and radiance based on the HITRAN absorption coefficient data base (Rothman et al. 1992). We use only the components of this software that allow line-by-line optical depth computations to be performed, removing all the superfluous routines and therefore speeding up the computations. The continuum contributions for self and foreign broadened water vapor absorption, carbon dioxide absorption and collision induced bands of nitrogen are included.

Description of SBDART-MOD

In SBDART-MOD, scattering is computed using the SBDART modeling framework described above, while gaseous absorption optical depth is computed based on line-by-line computations, converted through the correlated-k method. Cloud and aerosol absorption and scattering optical depth is based on their concentration and optical properties.

A main feature of SBDART-MOD's infrared component is its capability to accurately compute the spectral radiation field at reasonable computing time costs compared to line-by-line models. To achieve a significant computing time reduction, we have used three different techniques. First, we have significantly reduced the spectral line data base through elimination of extremely weak absorption lines. The culling process we have applied reduces the HITRAN96 data base by about a factor of 20. Second, we are using computing techniques to minimize the data retrieval requirements. Third, we are using a more efficient quadrature over the spectral band as a result of the k-distribution algorithm.

For illustration, we have applied a modified correlated-k approach to the AIRS (Atmospheric InfraRed Sounder) spectral channels, which are only a few cm^{-1} wide. In this case, the statistical distribution of overlapping lines does not generally follow the random-overlap assumption used by Lacis and Oinas (1991). To address this issue, we have developed a number of alternative methods. The first one splits the channels into a number of sub-bands, with the goal of separating the overlapping lines as much as possible. This approach produces significant improvements in accuracy when a small number of sub-divisions are adequate to separate overlapping spectral features. The second approach involves splitting of the band, but this time based on the strength of the absorption. The third approach called the double correlated-k, orders the absorption based on the main absorber in that band. These various methods are chosen to minimize the difference between our computations and line-by-line computations.

In the visible and near infrared part of the spectrum, computing the correlated-k coefficients line by lines involves a multitude of lines, and therefore is extremely computer time consuming. It is, however, possible to speed up the correlated-k computations using a pre-calculated data base. In this case, a large number of line-by-line computations are performed for many different cases (e.g., vertical temperature and water vapor distributions, cloud and aerosol conditions) and correlated-k coefficients are computed from this data base. With such a data base approach we have a factor 100 improvement in speed for a transmittance accuracy of 0.005 in most wavebands, and better than 0.03 in regions of strong absorption due to two or more absorbers.

Besides gas absorption, the other optical parameters required to simulate radiation in the near-infrared are the solar spectral irradiance, surface albedo, and the optical thickness, single scattering albedo and asymmetry factor of Rayleigh scattering, aerosol and clouds. These parameters have been adopted from the physical models in SBDART.

Validation for Clear and Cloudy Sky

We calculated radiance using SBDART-MOD and LBLRTM for clear sky conditions without aerosols. For ease of comparison we present the results in terms of equivalent brightness temperature. The radiances calculated by LBLRTM were convolved with the AIRS trapezoidal filter function. Shown in Figure 1 is the difference between TB calculated with LBLRTM and SBDART-MOD. More than 98% of AIRS infrared channels have brightness temperature differences (ΔT_R) less than 1.0 K. However, there are some strong O_3, H_2O, and CO_2 absorption bands with differences as large as 3 K. These large discrepancies occur mainly within the wavenumber regions that have significant absorption from overlapping spectral bands of two or more molecular species.

To address this issue of overlapping and uncorrelated absorption lines, we divided each of these channels into two equal sub-bands. The correlated-k coefficients were calculated separately for each of the resulting sub-bands and used as inputs to SBDART-MOD. The brightness temperature difference of the 1290 cm^{-1} and 1355 cm^{-1} channels are reduced to negligible levels when four sub-bands are used.

For validation of the model's multiscattering capability, we used it to compute radiances for cirrus clouds. The cloud optical depth calculations ranged from 0.1 to 5.0. Cirrus clouds were composed of spherical ice particles with an effective radius of 106 μm.

We derived the required line-by-line results by first using LBLRTM to calculate the optical thicknesses of gaseous absorption at each atmospheric layer, at a spectral resolution of 1000 samples in each AIRS infrared channel. The radiances were then calculated by running DISORT on each of the 1000 spectral points and convolving the result with the AIRS filter function. These calculculations used the same cloud parameters as used in the SBDART-MOD runs. We have repeated the line-by-line calculations at even higher spectral resolution and have obtained identical results, indicating that the Beer's law applies in these small wavenumber intervals. The solar zenith angle in the line-by-line and SBDART-MOD calculations is 30 degrees.

Since the line-by-line calculations are rather time consuming, we limit our comparisons to a set of 24 representative AIRS channels. Figure 2 shows (ΔT_R) between the line-by-line and SBDART-MOD computations for cirrus at the range optical depth mentioned above. These results indicate that in most AIRS channels the presence of clouds affects (ΔT_R) in the direction of reducing the discrepancy. This effect seems most pronounced in the 1028 cm^{-1} channel, which contains strong ozone and water vapor lines. The magnitude of the (ΔT_R) decreases from 1.2 K to 0.1 K as the cirrus cloud optical depth is increased from 0 to 5.

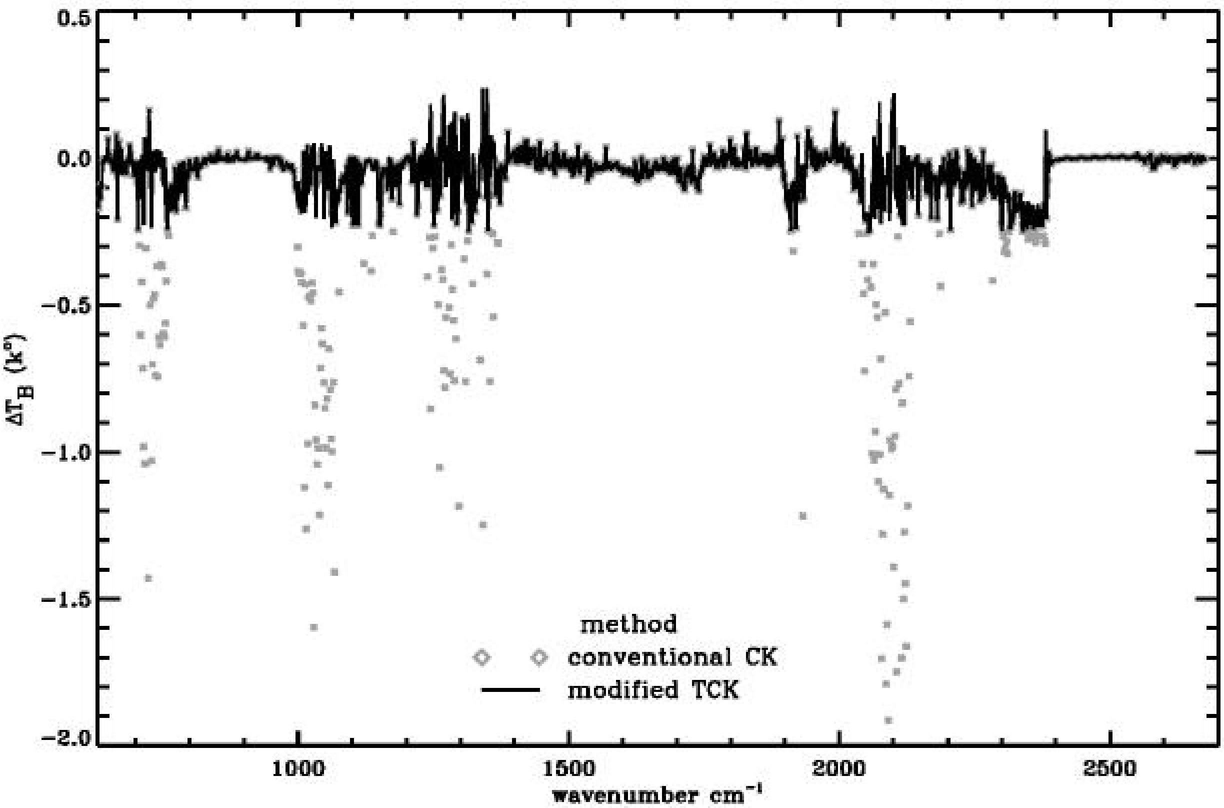

Figure 1. Brightness temperature difference (LBLRTM—SBDART-MOD), clear-sky conditions (K).

Discussion and Conclusion

The high spectral resolution of the AIRS infrared and other such sensors will provide a dramatic increase in the information available for the analysis of atmospheric structure. In developing SBDART-MOD, our main goal is to be able to analyze this information under general atmospheric conditions, including the effects of clouds and aerosols. To demonstrate how such an analysis may be carried out we have used SBDART-MOD to simulate the brightness temperature in the AIRS infrared channels for several cloud conditions over an ocean surface. The results of these calculations are shown in Figure 2.

Certainly, more research is required to develop these and other retrieval techniques that operate in the cloudy atmosphere. A cirrus cloud with optical depth as small as 0.1 can suppress the brightness temperature by 2.5 K. It is therefore essential to develop sensitive methods to detect thin cirrus clouds in order to carry out the AIRS program goal of determining temperature profiles within 1 K throughout the atmosphere.

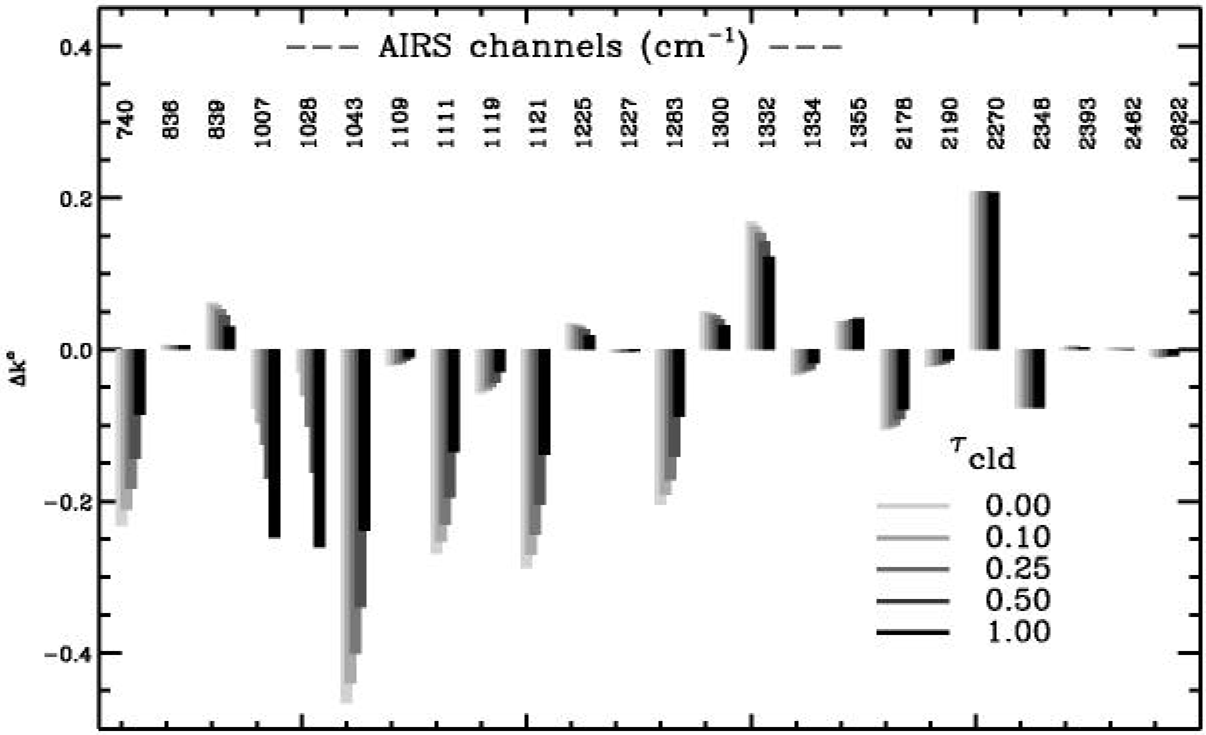

Figure 2. Brightness temperature difference (LBLRTM—SBDART-MOD), cirrus conditions (K).

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