High Spectral Resolution Radiative Transfer Model for IR and NIR Atmospheric and Cloud Remote Sensing Applications

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Introduction

The next generation of visible and infrared (IR) satellite sensors will require a new set of high-resolution radiative transfer models to accurately simulate observations and develop improved retrieval algorithms. Accurate high-resolution spectral models that can be used to investigate cloud/radiation properties to be provided by instruments such as the Atmospheric Infra Red Sensor (AIRS) or even the MODerate resolution Infrared Sensor (MODIS) are missing or cumbersome to use.

In this paper, we describe SBDIR, a newly developed computer code capable of predicting near-IR (NIR) radiation at high spectral resolution. SBDIR is based on a diverse set of physical models describing absorption, emission and scattering in the earth's atmosphere. Many of these models were adopted from our low-resolution radiative transfer model, SBDART (Ricchiazzi et al. 1998). In developing SBDIR, our main objective was to improve the spectral resolution of the SBDART model by incorporation of a detailed correlated-k gas absorption model (Goody 1952; Lacis and Hansen 1991) based on the HITRAN data base. The main attraction of the correlated k-distribution method is that it avoids the redundant spectral computations of line-by-line models. The k-distribution method takes advantage of the fact that the transmission within a band is independent of the spectral sampling order. Reordering 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. This improved numerical efficiency is especially important in SBDIR, since each quadrature point requires a solution to the multiple scattering radiative transfer equation.

SBDIR Overview

In SBDIR scattering is computed using the SBDART modeling framework (Ricchiazzi et al. 1998), while gaseous absorption optical depth is computed based on the Line-by-Line Radiative Transfer Model (LBLRTM) and converted through the correlated-k method. Cloud and aerosol absorption and scattering optical depth are based on their concentration and optical properties. A main feature of SBDIR is its capability to accurately compute the spectral radiation field at reasonable computing time costs compared to line-by-line models. The computing time reduction is achieved in three ways: 1) significantly reducing the size of the spectral line data base through elimination of very weak absorption lines; 2) using computing techniques to minimize the data retrieval requirements; and 3) using the k-distribution algorithm to reduce the computational cost of the spectral band quadrature.

Our goal is to be able to model the relatively narrow spectral channels of modern satellite sensors. For example, the spectral widths proposed for the AIRS sensor are only a few cm^{-1} wide. Applying the correlated-k algorithm to this situation is straight-forward except when there is strong absorption by more than one molecular species within the sensor channel. In this case, the statistical distribution of overlapping lines do not, in general, follow the random-overlap assumption used in previous applications of the correlated-k formulism (Lacis and Hansen 1991). In SBDIR, our approach is to split the problematic channels into a number of sub-bands, with the goal of separating the overlapping lines as much as possible. In most cases, this scheme produces significant improvements in accuracy.

Validation

Clear Sky

We calculated radiance using SBDIR, Moderate Resolution Atmospheric Radiance and Transmittance Model (MODTRAN) 3.5, 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. As shown in Figure 1, the

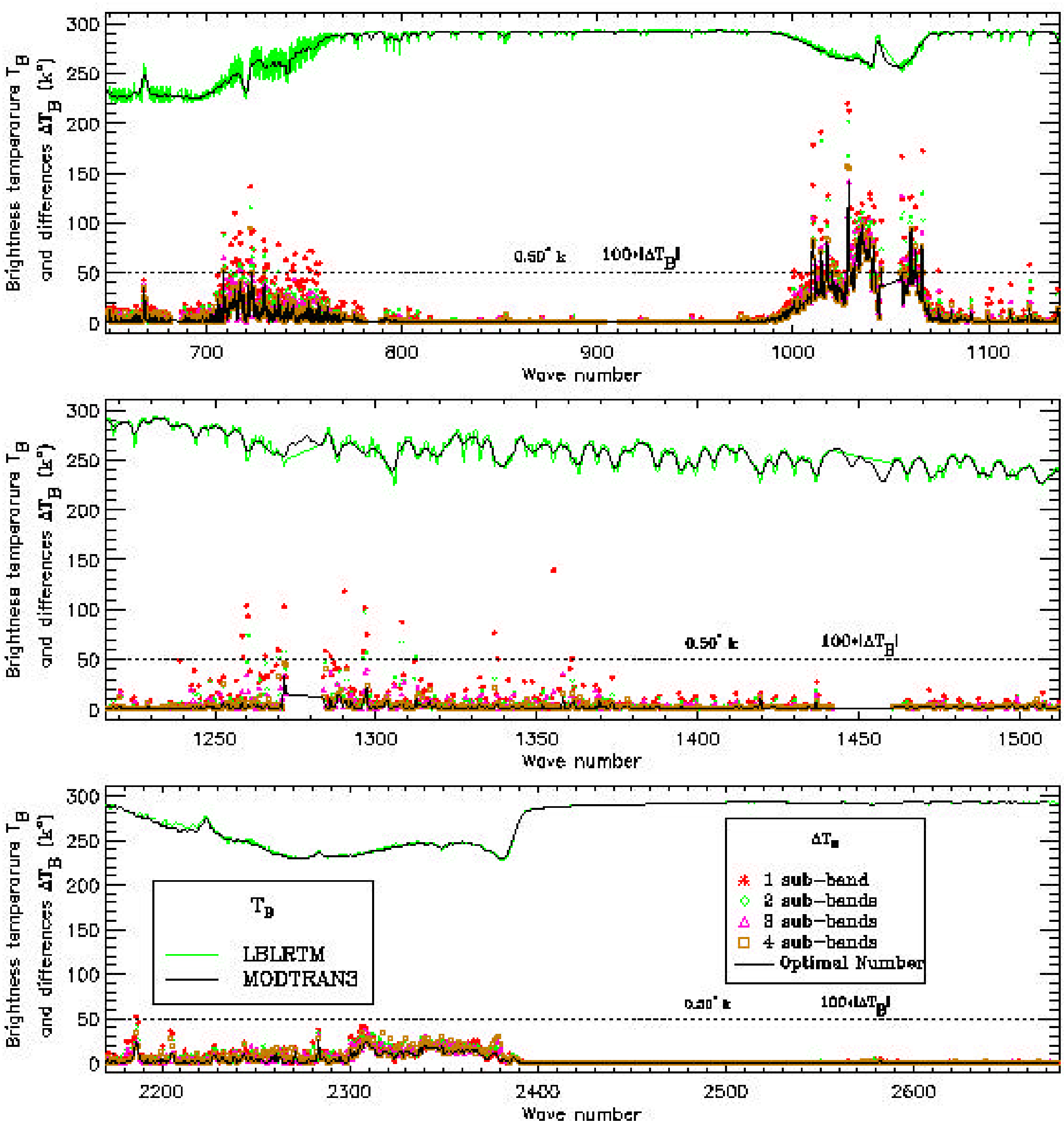

Figure 1. Brightness temperature calculated by LBLRTM (green), and MODTRAN3 (black) for all AIRS IR channels. Also shown at the bottom of each frame is the absolute difference in brightness temperature between SBDIR and LBRTM (multiplied by 100). In some AIRS channels the brightness temperature difference can be reduced significantly by subdividing into two or more sub-bands. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/shiren-98.pdf*.)

brightness temperatures calculated with LBLRTM and SBDIR are very similar. Results computed by MODTRAN 3.5 are close to the smoothed brightness temperatures calculated with LBLRTM or SBDIR in most AIRS channels. Also shown in Figure 1 is the difference between calculations with LBLRTM and SBDIR. More than 98% of AIRS IR 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.

In most of these spectral bands, the band-splitting approach was effective in reducing the level of discrepancy to acceptable levels.

Cloudy Sky

For validation of the model's multiscattering capability, we used it to compute radiances for cirrus clouds, mid-level clouds and low-altitude clouds. Cirrus clouds were composed of spherical ice particles with an effective radius of 106 μm, while the lower level clouds were composed of water droplets of effective radius 10 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 IR channel. The radiances were then calculated by running the Discrete Ordinate (DISORT) model on each of the 1000 spectral points and convolving the result with the AIRS filter function. These calculations used the same cloud and aerosol parameters as used in the SBDIR 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 SBDIR calculations is 30 degrees.

Because the line-by-line calculations are rather time consuming, we limit our comparisons to a set of 24 representative AIRS channels. Figure 2 shows the difference in brightness temperature, ΔT_R, between the line-by-line and SBDIR computations for 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. For example, in Figure 2a, 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.

Discussion and Conclusion

The high spectral resolution of the AIRS IR sensors will provide a dramatic increase in the information available for the analysis of atmospheric structure. In developing SBDIR, 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 SBDIR to simulate the brightness temperature in the AIRS IR channels for several cloud conditions over an ocean surface. The results of these calculations are shown in Figure 3. The IR spectrum is highly sensitive to cirrus cloud optical depth but less sensitive to typical variations of the optical depth of lower level clouds. Varying the cirrus optical depth between 0 and 5 produces a 30-K variation in the brightness temperature throughout most of the IR spectrum.

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.

References

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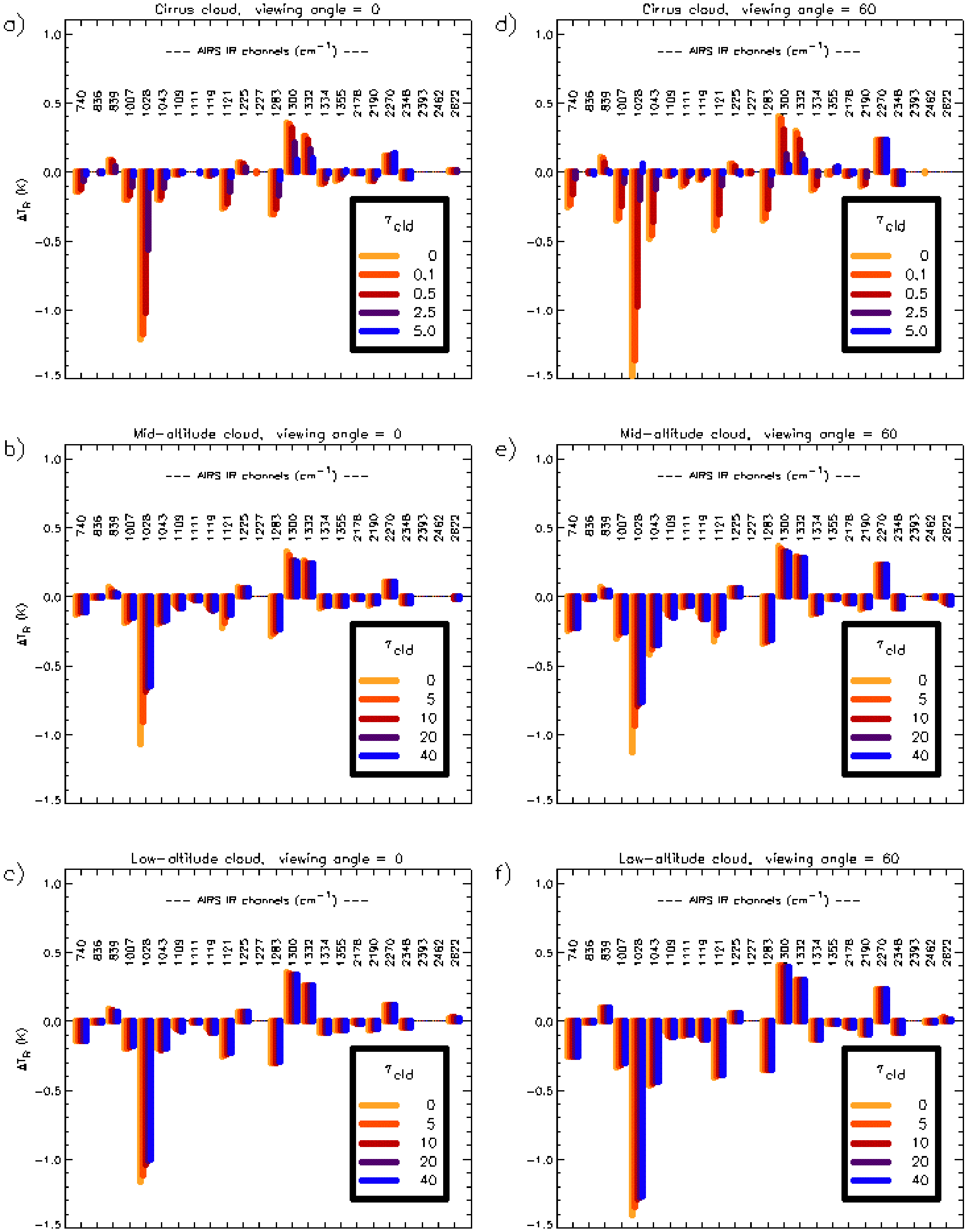

Figure 2. Brightness temperature difference between SBDIR and a line-by-line model for 24 representative AIRS IR channels. Results are shown for viewing zenith angles of zero (right) and 60 degrees (left), and for cirrus clouds (top), mid-level clouds (middle), and low-level clouds (bottom). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/shiren-98.pdf*.)

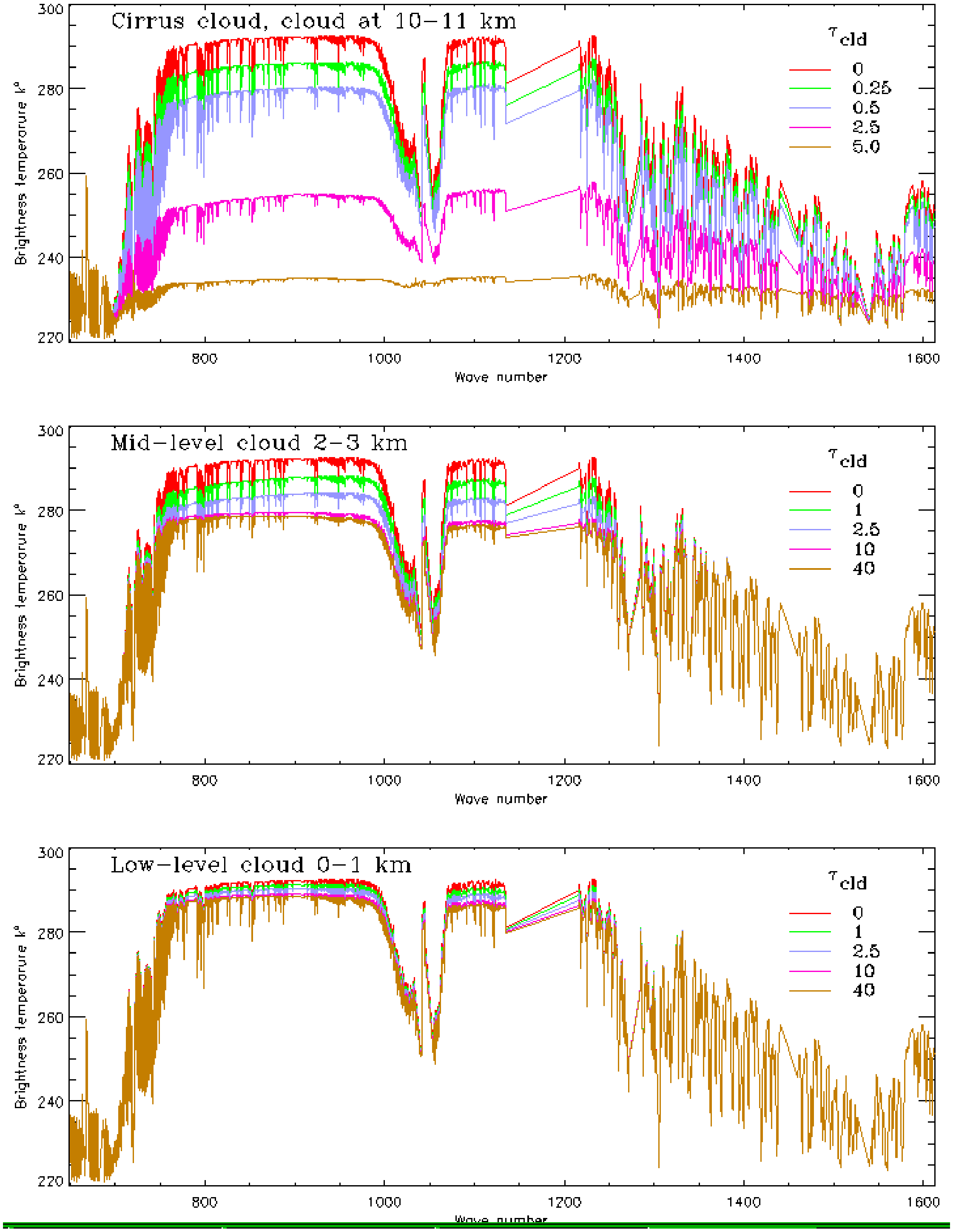

Figure 3. Brightness temperature computed by SBDIR for cirrus clouds (upper panel), mid-altitude clouds (middle panel) and low clouds (bottom panel). Cloud optical depth ranged between 0.1 and 5 for cirrus clouds and between 5 and 40 for the mid-altitude and low (water) clouds. In these calculations, the solar zenith angle and viewing nadir angle were both set to 30 degrees. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/shiren-98.pdf*.)