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

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The objective of this research effort is to develop radiative transfer models that are consistent with Atmospheric Radiation Measurement (ARM) Program spectral radiance measurements for clear and cloudy atmospheres. Our approach is to develop the model physics and related databases with a line-by-line model in the context of available spectral radiance measurements. The line-by-line model then functions as an intermediate standard to both develop and validate rapid radiative transfer models appropriate to GCM applications.

Line-by-Line Multiple Scattering Code: CHARTS

CHARTS (Code for High-Resolution Atmospheric Radiative Transfer with Scattering), J.-L. Moncet lead investigator, is now fully functional for applications in the thermal infrared. The code is optimized to calculate the spectral radiance and spectral transmittance for a scattering atmosphere with the viewing angle and position specified. These are the anticipated conditions under which the code will be applied to ARM spectral observations: ground, aircraft or satellite-based spectral radiance and transmittance measurements. CHARTS restricts the multiple scattering calculation to the atmospheric regime in which the scatterer is included. A line-by-line radiative transfer model, in this case LBLRTM, is used for the non-scattering atmosphere in the altitude regime above the clouds, providing the spectral dependent boundary condition for the CHARTS calculation.

Figure 1 demonstrates the effects on the downwelling spectral radiances due to multiple scattering from an optically thin cirrus cloud in the altitude regime from 10-12 km for a range of cloud water paths. This case[a] is consistent with downlooking data taken with the high spectral resolution interferometer sounder (HIS) (Smith et al. 1983) from 20 km and with simultaneous data taken with the atmospheric emitted radiance interferometer (AERI) on the ground as part of the Spectral Radiance Experiment (SPECTRE). Ackerman has calculated the spectral scattering parameters for ice spheres with a 15-μ mode radius. The cloud, covering the altitude regime from 10-12 km, has a mass path 5 g/m^2. Validations are being performed using these data sets and comparing the results of our model with results from more rapid but less rigorous treatments of the multiple scattering. Extension of the model to solar spectral transmittance measurements is being initiated.

(a) S. T. Ackerman, private communication, 1993

Radiation Models: LBLRTM and RRTM

Extensive effort has gone into two aspects of the Line-by-Line Radiative Transfer Model (LBLRTM): 1) applying the model to real-time spectral validations for ARM measurements, including the implementation of an fft package to model spectral instrument functions and 2) adapting the model to provide the necessary interface with CHARTS. LBLRTM is a vectorizable line-by-line model based on the FASCODE algorithms and includes the capability to calculate atmospheric fluxes and heating rates. The model has also been adapted to function as the forward model in a retrieval algorithm to retrieve atmospheric profiles of temperature and trace gas profiles from high-resolution spectral radiance data. LBLRTM has been extensively validated with HIS measurements, e.g., Clough et al. (1992).

In the course of developing a rapid radiative transfer model (RRTM), we have performed spectral band comparisons of cooling/heating rate results from the NASA-AMES/Penn State model (Toon et al. 1989), with line-by-line

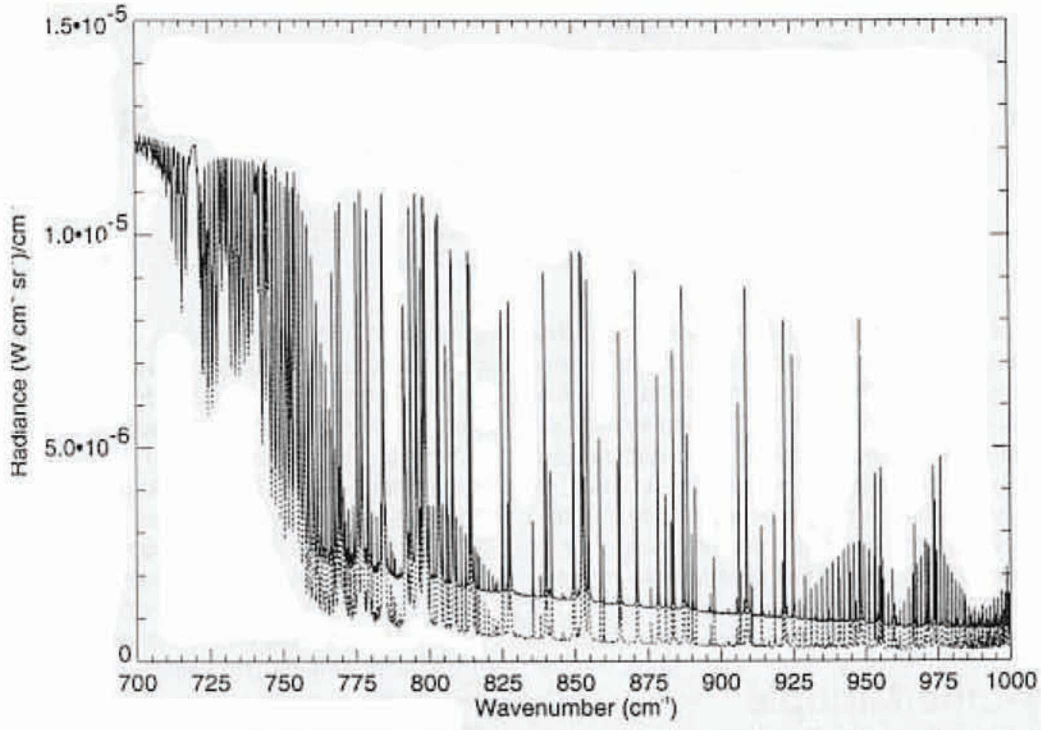

Figure 1a. The downwelling spectral radiance at the surface for an atmosphere with a 10-12 km optically thin cirrus cloud with 15 μ mode radius and mass path of 5 g/m² (solid curve) and for a clear atmosphere (dotted curve).

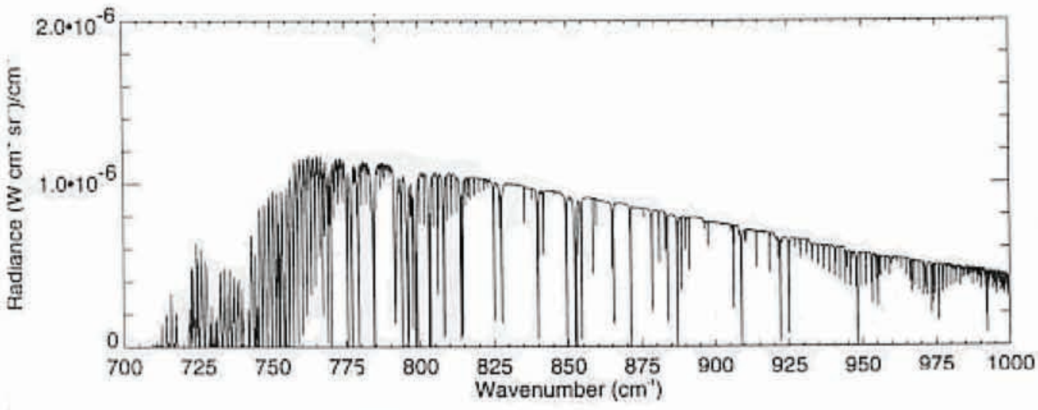

Figure 1b. Difference in spectral radiances of Figure 1a, cloud - clear.

results obtained from LBLRTM. The results at this stage of the effort indicate that the treatment of the continuum and the k-distributions for the line contribution in this rapid model are not consistent with LBLRTM. At the surface, there is a difference of 10 w/m^2 in the net flux for the mid-latitude summer atmosphere. Since the goal of the current research effort is to attain accuracy performance from the rapid model that is consistent with LBLRTM and measurements to be taken at the ARM sites, an initiative is underway to develop a new RRTM that uses a continuum formulation and k-distributions that provide results as consistent as possible with the line-by-line calculations.

Revised Continuum Model

The water vapor continuum plays an important role in atmospheric radiative transfer, providing increased opacity between spectral lines over the full spectral region from the microwave to the visible. The continuum has a significant influence on atmospheric fluxes and cooling rates. Additionally, the continuum is important to the physical solution of the inverse problem, the remote sensing of atmospheric state to retrieve temperature, water vapor, surface properties and other state parameters.

The continuum has two components: the self-broadened continuum, dependent on the square of the partial pressure of water vapor, and the foreign-broadened continuum, dependent on the product of the water vapor partial pressure and the dry air pressure. As a consequence, the self-broadened continuum tends to be more important in the lower atmosphere, while the foreign-broadened continuum tends to be more important in the middle to upper troposphere.

A comprehensive continuum model based on a single line shape for all transitions from the microwave to the visible has provided generally acceptable results (Clough et al. 1989 and Clough et al. 1980; hereafter CKD). The nadir and zenith spectral radiometric measurements with the University of Wisconsin HIS instrument have been particularly useful in establishing the general level of accuracy for the continuum. For most spectral regions, the apparent error in the continuum is of the order of 10% or less. The term "apparent" is used because of the difficulty of unambiguously characterizing the atmosphere, particularly with respect to aerosol loading and to sub-visual cloud effects. However, for special conditions of atmospheric state, measurements indicate that for specific and very limited spectral regions, errors in the CKD continuum may be significant.

To address this situation and to improve overall accuracy of atmospheric radiance calculations, we have developed an improved but preliminary water vapor continuum model, designated CKD-1. The approach has been to more carefully model the laboratory measurements of Burch and to validate the refined model with up- and down-looking spectral radiance data. The full data set of Burch and coworkers (1985, 1984, 1981) has been reanalyzed using a self-consistent approach for the contribution of local lines. In contrast to the earlier model, this reanalysis provides full consistency with the line shape decomposition used for the LBLRTM model.

Our intention had been to develop a new water vapor line shape which, when applied to all water vapor lines, would provide agreement with the laboratory and atmospheric measurements. Evidence is mounting that, for the accuracy required for ARM radiation measurements and for climate change considerations, a continuum model based either on semi-empirical analytic line shape functions (CKD) or those obtained from collisional theory is not likely to prove adequate. Using the quasistatic approximation, Ma and Tipping (1992) have developed a line shape which they have used to obtain a self and foreign water vapor continuum.[a] In our judgment, their results are not sufficiently accurate to be used directly to describe the continuum; a calculation using the molecular potential of the water molecule would not be expected to be valid to the required level of accuracy.

The continuum absorption coefficient for a homogeneous path, k_c, may be expressed in terms of the self and foreign continuum coefficients, $\tilde{C}_s$ and $\tilde{C}_f$, as

$$k_c = v \tanh(hcv/kT)\left[\left(\rho_{h_2O}\right)\tilde{C}_s(T) + \left(\rho_{air}/\rho_o\right)\tilde{C}_f(T)\right]$$

where v is the photon wavenumber value, T is the temperature, ρ_{h_2O} is the density of water vapor, ρ_{air} is the density of dry air and ρ_o is the reference density at one atmosphere.

Figures 2a and 2b provide the self and foreign continuum coefficients, respectively, for the longwave region. The symbols represent Burch's measurements with the local

(a) Private communication.

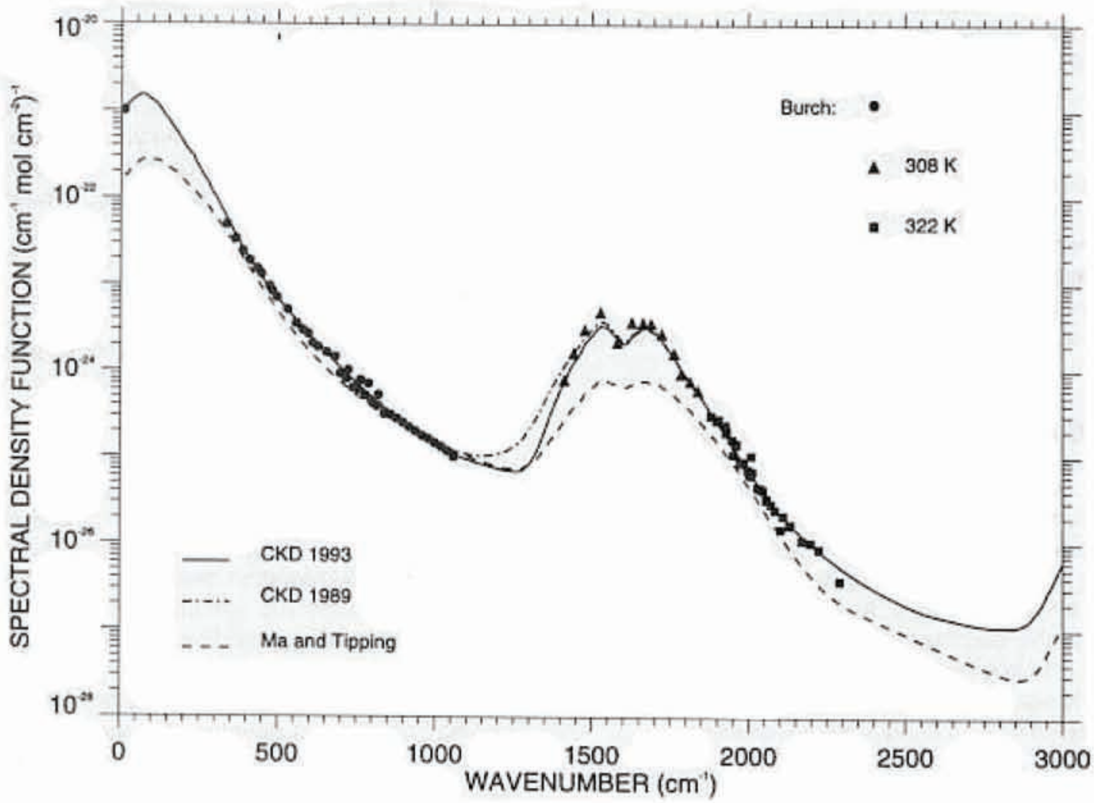

Figure 2a. The water vapor continuum coefficients at 296K for the self-broadening case.

line contribution removed using the LBLRTM local line definition at the indicated temperature. In both the self and foreign cases the CKD continuum does not model the data well at the low wavenumber side of the ν_2 band in the 1300 cm^{-1} region. The CKD-1 continuum has been analytically adjusted to improve agreement. A validation of this modification is provided in Figure 3.

Figure 3a provides the upwelling spectral radiances measured at 20 km with the HIS instrument, Figure 3b provides the spectral residuals with the CKD continuum, and Figure 3c provides the spectral residuals with the revised CKD-1 continuum. Significant improvements in the spectral residuals are apparent. The remaining residuals in the 1300 cm^{-1} region are not attributable to the continuum since removal of the continuum does not reduce these residuals (which are most likely attributable to an incorrect methane profile). The upwelling radiance provides an important validation of the treatment of the temperature dependence of the continuum since the radiation is emanating from altitude regimes associated with colder temperatures. The temperature and water vapor profiles have been obtained from radiosonde measurements; the profiles for the uniformly mixed species have been obtained from climatology; and the line-by-line calculations are from LBLRTM. Similar conclusions may be drawn from the downwelling radiances from HIS ground-based observations. Preliminary results from laboratory measurements by Kulp[a] indicate essential confirmation of the CKD-1 continuum from 700 - 1300 cm^{-1} at 296K.

The CKD water vapor continuum model provides calculated spectra in significantly better agreement with observed

(a) Private communication, 1993.

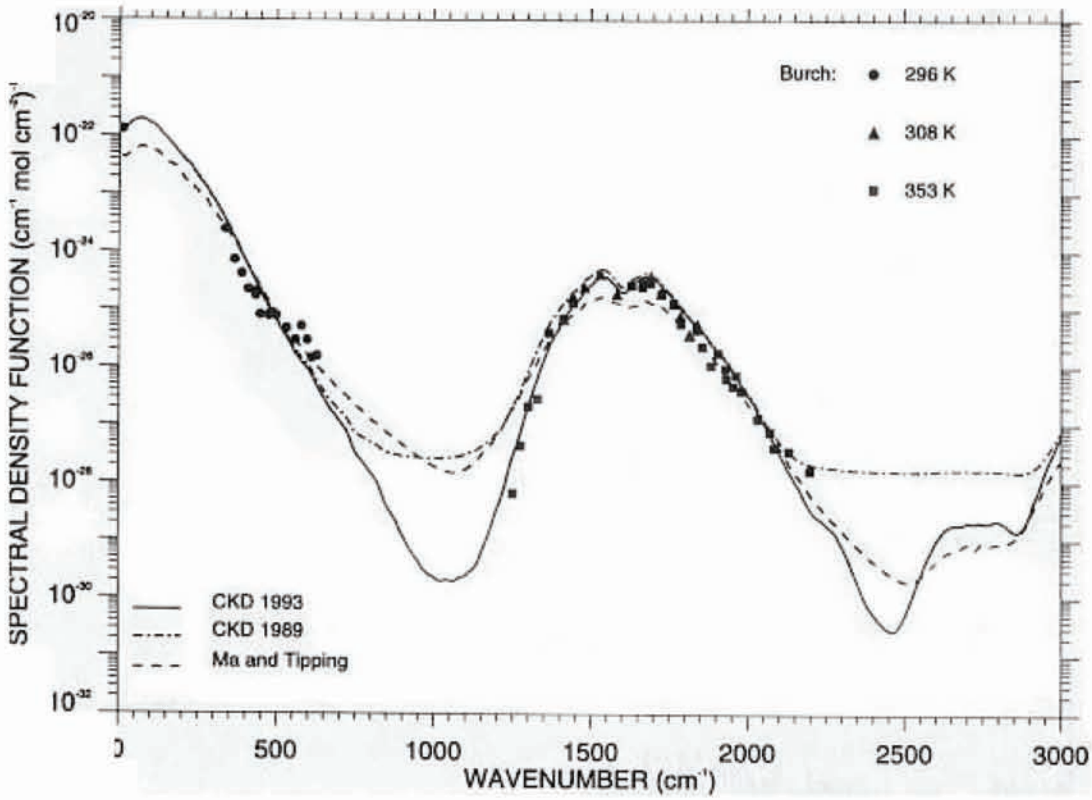

Figure 2b. The water vapor continuum coefficients at 296K for the foreign-broadening case.

spectral radiance data than the Roberts et al. model (1976), which is used in many radiative models for studies related to climate change. Because of its analytical form the Roberts et al. model has a certain appeal related to simplicity of application; nevertheless, the model reflects incorrect physics, does not properly treat the foreign continuum, and is not sufficiently accurate to meet present requirements.

The CKD-1 continuum is available to the general scientific community in a stand-alone program via anonymous ftp at AER. The numerical nature of the CKD model makes it readily tractable for application to correlated k-distribution radiative transfer models. The model will continue to undergo validation and refinement. We anticipate that the spectral radiance data to be obtained at the Western Pacific ARM site will be especially valuable in assessing continuum model performance for tropical atmospheres, a matter of particular importance for climate considerations.

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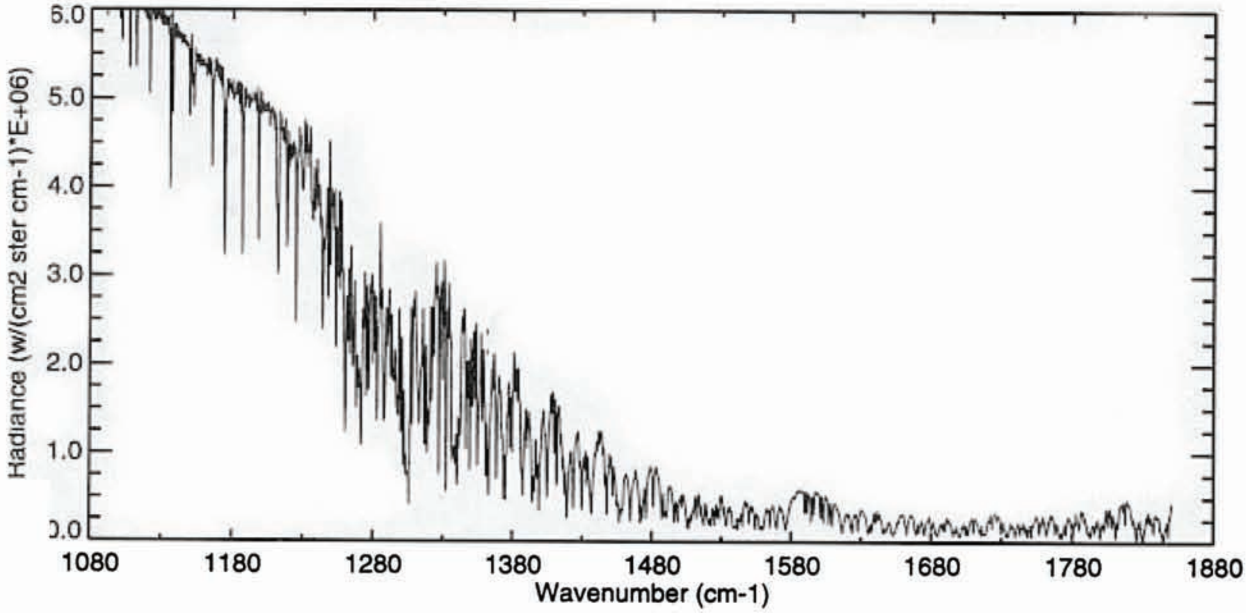

Figure 3a. Spectral radiances from the 14 April 1986 HIS measurement from 19.6 km.

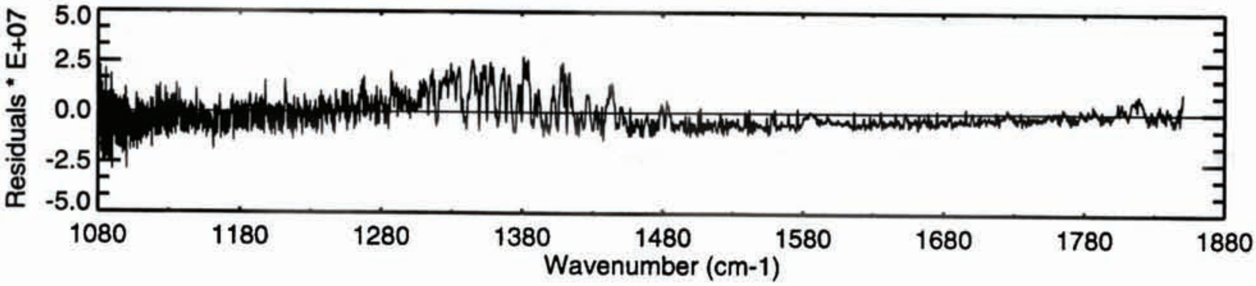

Figure 3b. Spectral residuals from the difference of the observation of Figure 3a and an LBLRTM calculation using the CKD continuum.

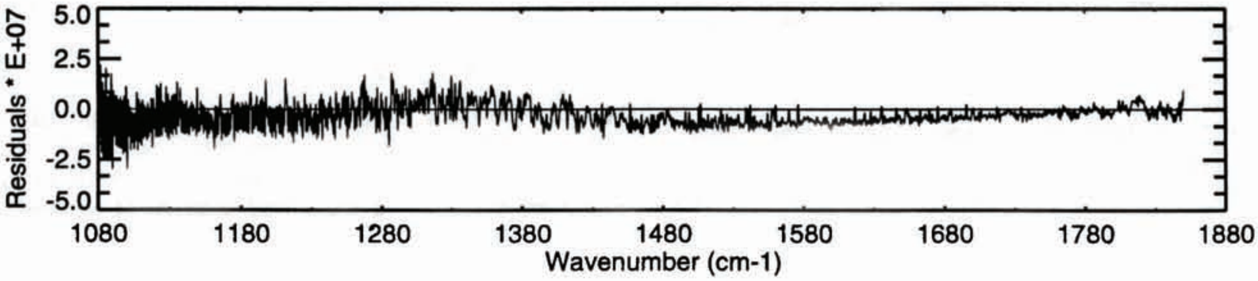

Figure 3c. Spectral residuals from the difference of the observation of Figure 3a and an LBLRTM calculation using the CKD-1 continuum.

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