A Narrow Band Longwave Radiation Model Based on Parameters Fitted to Line-by-Line Radiative Transfer Model

J. X. Warner and R. G. Ellingson
University of Maryland
College Park, Maryland

Introduction

The results from the Intercomparison of Radiation Codes Used in Climate Models (ICRCCM) (Ellingson et al. 1991) showed about ±2% differences in flux calculations between the narrowband models and line-by-bine models. Narrowband and broadband model calculations of downwelling radiance showed similar discrepancies with observations from the SPECTral Radiation Experiment (SPECTRE, see Ellingson and Wiscombe 1996) and the Atmospheric Radiation Measurement (ARM) Program (Ellingson et al. 1995). Recent experiments have produced radiation and auxiliary data sets that allow more detailed tests of models. Hence, these experiments, along with other advances in the radiation field, provide the possibility for the development of more accurate radiative transfer models. The thrust of this study is to use these developments to develop an accurate model of longwave radiative transfer for eventual use in climate applications.

The Malkmus (1967) statistical band model is often used in narrowband models to calculate atmospheric fluxes and heating rates. However, the Malkmus model is insufficient to describe the dependence of water vapor transmittance on absorber amount in all spectral regions (Warner 1997). However, we found a relatively simple modification of the Malkmus formulation allowing fits to the LBLRTM (Line-by-Line Radiative Transfer Model, Clough et al. 1989) transmittances within 0.01 rms for more than 97% of the 10 cm^{-1} spectral intervals across the entire longwave spectrum. Heating rates calculations based upon the new transmittance formulation show better agreement with LBLRTM calculations than those based upon line parameters alone.

The total transmittance by water vapor includes the effects of the so-called water vapor continuum. This continuum is inexorably tied to the strengths, shapes, and distributions of the spectral lines. The usual band model approach of using asymptotic limits with line parameters or the fitting approach of Lacis and Oinas (1991) cannot by themselves separate out the continuum effects. Thus, those models require the determination of an empirical continuum for each spectral interval that cannot necessarily be traced to models of the overall continuum.

Recently, Clough et al. (1989) formulated a description of the continuum that ties the spectral lines to laboratory continuum and atmospheric observations. This was followed by a new line-by-line model that employs a truncated Voigt line profile with line intensities modified to account for the water vapor continuum (Clough et al. 1992). We have used LBLRTM, with their most recent version of the continuum (CKD_2.1), to derive a new band model formulation that includes this continuum in a consistent manner.

We began this study by empirically developing a new formulation that provides better agreement with LBLRTM calculations for both the homogeneous transmittances and the heating rates with contributions from the water vapor line absorption only. We then included the continuum effect that is defined consistently with LBLRTM CKD_2.1 continuum.

Transmittance Model for Water Vapor Line-Only Effects

We use the following equation to determine the dependence of transmittance on the absorber amount,

$$T(u) = \exp\left\{-\left[\sqrt{2m_1u + m_2^2} - m_2\right]\right\} \Big/ \cosh(m_3u) \qquad (1)$$

where u is the precipitable water. The pressure and temperature-dependent parameters m_1, m_2, and m_3 are determined by a non-linear least squares fit of the LBLRTM calculations.

This representation of the transmittance is simply the Malkmus transmittance divided by $\cosh(m_3u)$. This term's function is to increase the slope of transmittances with respect to absorber amount at both intermediate low and high values relative to that of the Malkmus model alone. It empirically compensates the oversimplified assumptions made in deriving the Malkmus model, namely Lorentz lines with an exponentially tailed s^{-1} line-strength distribution, and a homogeneous distribution of line-strengths from interval to interval. Note that the variation of line strength and half-width from spectral regions surrounding a given band can be large.

The determination of the coefficients, temperature and pressure variation and the application of the homogeneous transmittances to the inhomogeneous atmosphere are described in detail by Warner (1997). In the model calculations, the integrations over altitude and angle follow Ellingson and Gille (1978).

Figure 1 shows the altitude and spectral distributions of downward flux differences between our models and LBLRTM due to H_2O lines only for the McClatchey et al. (1972) midlatitude summer atmosphere. The upper panel represents the results for the original model that uses the Malkmus formulation; the lower panel represents the new model. In the upper panel for altitudes below 5 km, the error bands of different signs in the 500 to 1300 cm^{-1} spectral region partially cancel when spectrally integrated. Therefore, even when the spectrally integrated fluxes calculated by the Malkmus model are accurate, this does not guarantee a good prediction of a future state unless the physics is modeled correctly, because such spectral cancellations are not guaranteed. As shown in the lower panel, the new model results do not rely on the cancellation of the errors, and the accuracy of downward fluxes increased over the entire spectral range.

Continuum Absorption

The continuum absorption in the new band model was developed following that defined by Clough et al. (1989) and used in LBLRTM. Clough's continuum absorption is defined consistently with the water vapor line absorption based on the assumption that the continuum is due to the absorption

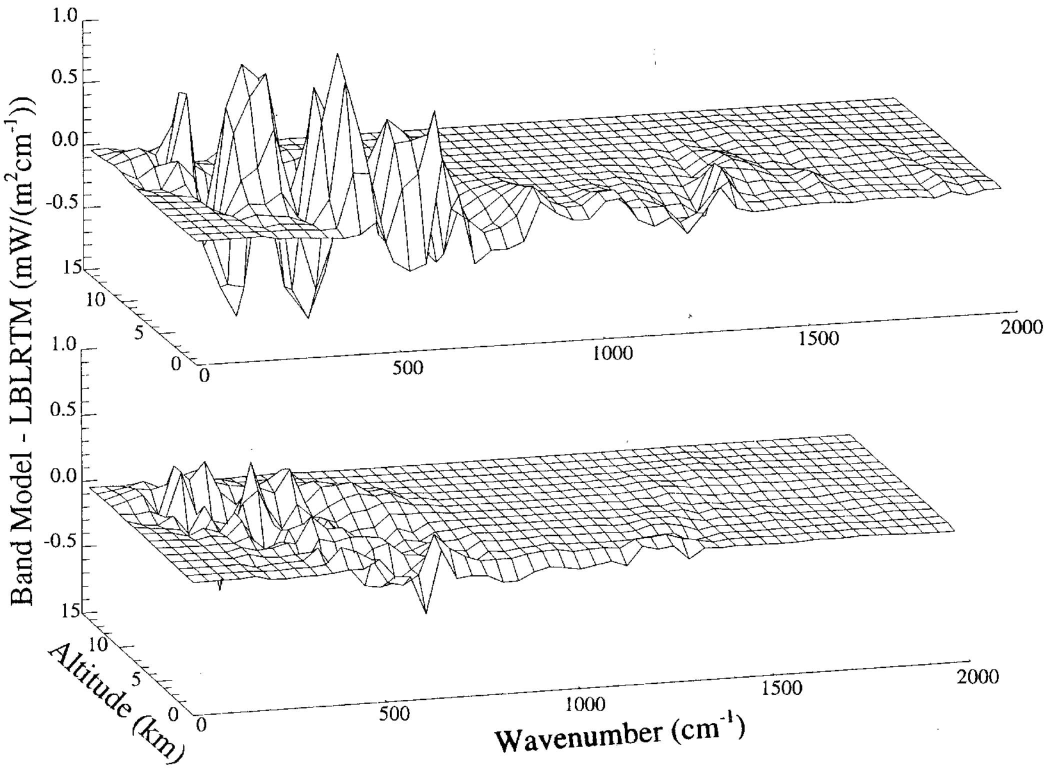

Figure 1. The spectral and altitude distributions of the differences (mW/(m^{2}cm-1)) between downward fluxes calculated from our models minus LBLRTM for H_2O lines only with the McClatchey et al. (1972) midlatitude summer atmosphere.

from far wings of the absorbing lines. Note that in LBLRTM, the water vapor lines are cut off at ±25 cm^{-1} from the line centers, and the absorption outside that range is calculated as continuum absorption.

Because the absorption by water vapor lines in our new transmittance model is determined from that of LBLRTM, which is consistent with the continuum absorption, the continuum absorption coefficients at standard density can be retrieved directly from LBLRTM. For the definition of Clough's continuum and its formulation, please see Clough et al. (1989). The pressure variation is linear based on the definition of the coefficients, i.e., the self-broadened coefficient is linear in the water vapor pressure and the foreign-broadened coefficient is linear in the pressure of the other atmospheric gases.

The temperature variation of the continuum coefficients in LBLRTM includes the contribution from both the temperature variation of the continuum and the temperature variation of the radiation term. The temperature variation of the continuum coefficients used in the narrow band model is fitted from the temperature-corrected coefficients of LBLRTM. For the self-broadened coefficient, we adopt the formulation

$$C_s^0(T) = C_s^0(T_0)\exp(-a(T-T_0)) \qquad (2)$$

where a is determined from LBLRTM data and T_0 was chosen at 296 K. Although the foreign-broadened continuum is assumed not to vary with temperature, the temperature variation of the radiation field was assumed to be given as,

$$C_f^0(T) = C_f^0(T_0)(a + b(T-T_0) + c(T-T_0)^2) \qquad (3)$$

where a, b and c are coefficients fitted to LBLRTM temperature-corrected coefficients. In addition, because the coefficients $C_s^0(T)$ and $C_f^0(T)$ are scaled by the density, the following form is incorporated into the band model continuum absorption coefficient,

$$k_{ci}(T) = C_{si}^0(T)(T_0/T)(e/p_0) + C_{fi}^0(T)(T_0/T)(p/p_0) \qquad (4)$$

where the subscript *I* refers to the *i*th interval in the band model, $T_0 = 296.0\,K$ and $p_0 = 1013.0$ mb.

Flux and Cooling Rate Calculations

Fluxes and heating rates due to absorption by both lines and continuum were calculated for the five McClatchey standard atmospheres. Figure 2 shows the differences of upward, downward, and net fluxes between our models and LBLRTM for the midlatitude summer atmosphere. The original model results are shown by the long-dashed lines, and the new model results are dotted lines. The upward flux differences at the top of the atmosphere were reduced from 5.3 to 0.8 W/m^2, and the absolute differences of the downward flux at the surface were reduced from 11.4 to 1.1 W/m^2.

Figure 3 shows the spectral distribution of heating rate differences between the band models and LBLRTM due to both water vapor line and continuum absorption for the McClatchey midlatitude summer atmosphere. Similar to Figure 1, the upper panel represents the original model results, and the lower panel represents the new model. The new model agrees with LBLRTM on the heating rate calculations across the entire spectrum to within ±0.25 mK/(day cm^{-1}). The strong cancellation of error bands found in the original model in the 150 - 1000 cm^{-1} spectral region was reduced almost completely by using the new model.

Summary

The Malkmus model is insufficient to describe the dependence of water vapor transmittance on absorber amount in all spectral regions. Flux and heating rate calculations based upon the new transmittance formulation show better agreement with LBLRTM calculations than those based upon the Malkmus formulation and the line parameters alone.

Because the new formulation of line transmittance follows directly from that used in LBLRTM, the addition of the CKD_2.1 water vapor continuum follows the same manner used in LBLRTM, thereby allowing for a narrowband transmittance model with the same line-continuum consistency used in LBLRTM. The downward fluxes calculated from the water vapor model agree with LBLRTM to about 1 W/m^2 for all McClatchey et al. (1972) atmospheres. In addition, the accuracy of the new model does not rely on the cancellation of the errors between spectral intervals when the total fluxes and heating rates are calculated.

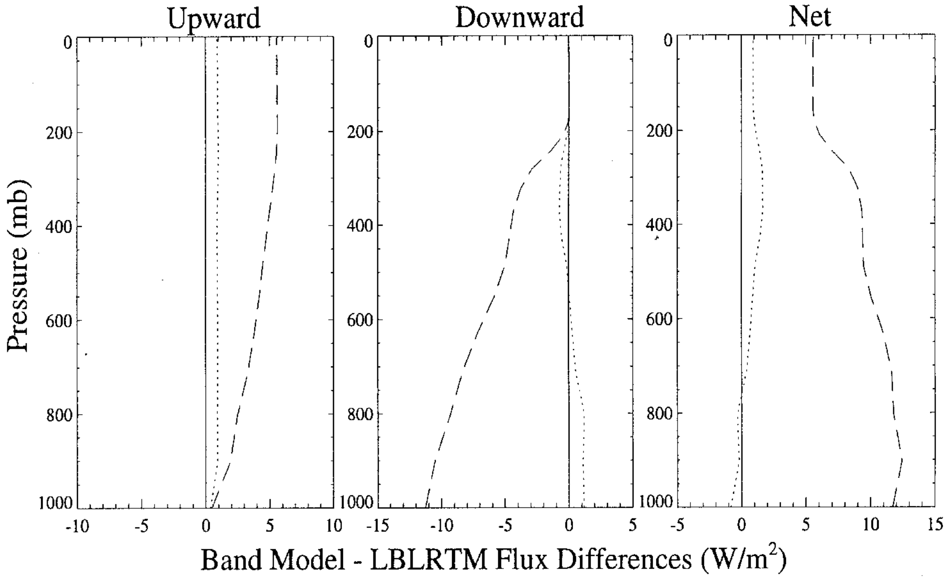

Figure 2. The flux differences between the original model and LBLRTM (long-dashed lines) and the new model and LBLRTM (dotted lines) for the upward, downward, and net fluxes due to water, vapor line, and continuum absorption for the McClatchey et al. (1972) midlatitude summer atmosphere.

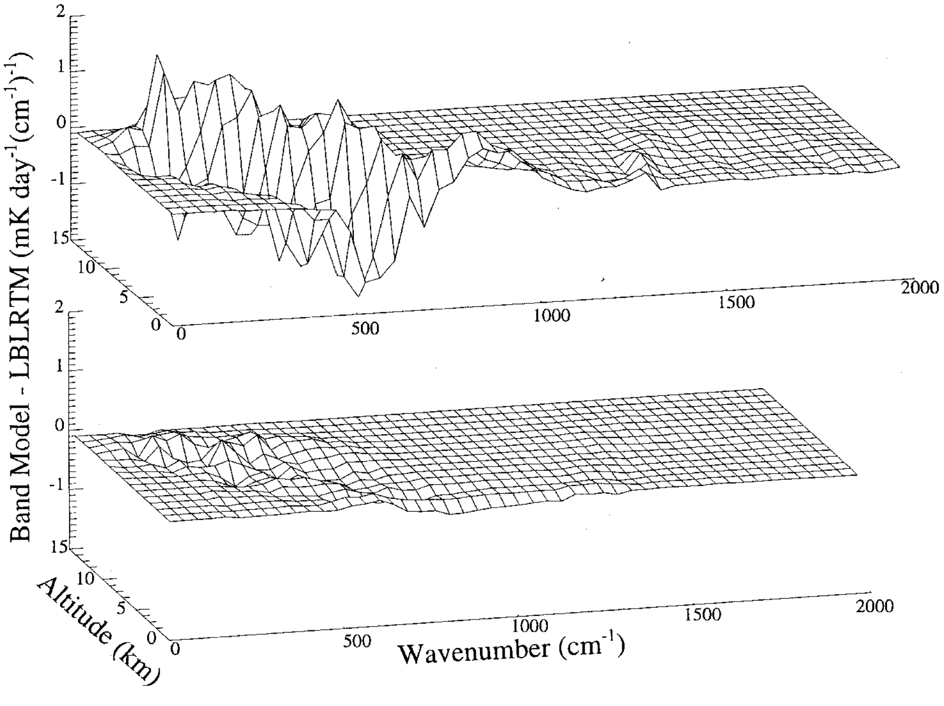

Figure 3. The spectral and altitude distributions of the differences (mK day^{-1} (cm^{-1})$^{-1}$) between our models and LBLRTM heating rates due to the combined effects of H_2O lines and the continuum for the McClatchey et al. (1972) midlatitude summer atmosphere.

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