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

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Introduction

The results from the Intercomparison of Radiation Codes Used in Climate Models (ICRCCM) (Ellingson et al. 1991) showed about ±5% differences in flux calculations between the Narrow Band Models (NBMs) and Line-By-Line (LBL) models. Narrowband and broadband model calculations of downwelling radiance showed similar discrepancies with observations from the SPECTral Radiation Experiment (SPECTRE) and Atmospheric Radiation Measurement (ARM) program (Ellingson et al. 1995).

The Malkmus (1967) statistical band model is often used in narrowband models to calculate atmospheric fluxes and heating rates. However, the model is based on assumptions that oversimplify the absorbing line properties. The model parameters are usually determined by requiring an exact fit of the model to observations or spectral line data in the weak and strong line, non-overlapping absorption limits (Goody 1964). Lacis and Oinas (1991) showed that more accurate transmittances could be obtained by determining the model parameters through the least-squares fits of LBL calculations. They concluded that using the newly fitted parameters the Malkmus model represents LBL transmittances with improved accuracy in most parts of the longwave spectrum. Nevertheless, there are many spectral regions where the Malkmus model does not accurately reproduce the LBL results even with such least-square fits.

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 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 observations. This was followed by a new LBL 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 this model, the Line-By-Line Radiative Transfer Model (LBLRTM), with their most recent version of the continuum (CKD_2.1) to derive a new band model formulation that can include this continuum in a consistent manner.

We began by testing the accuracy of transmittances calculated with the Malkmus band model fitted to LBLRTM transmittances without the continuum, and we found that it does not sufficiently describe the dependence of transmittance on the precipitable water. We then empirically developed a new formulation that provides better agreement with LBLRTM calculations for both the momogeneous transmittances and the heating rates. This study so far has only included the water vapor line absorption, which is defined consistently with LBLRTM CKD_2.1 continuum.

Malkmus Model Transmittances with Fitted Parameters

The Malkmus model transmittance for a homogeneous path with precipitable water u may be expressed as

$$T(u) = \exp\left\{-\left[\sqrt{2m_1 u + m_2^2} - m_2\right]\right\} \tag{1}$$

The parameters m_1 and m_2 were obtained by a non-linear least-squares fit of the model to the LBLRTM transmittances at 45 discrete precipitable water amounts ranging from 10^{-5} to 20 cm.

A typical example of the least squares fit to LBL data is shown in Figure 1 for the 430 - 440 cm^{-1} spectral region at a pressure

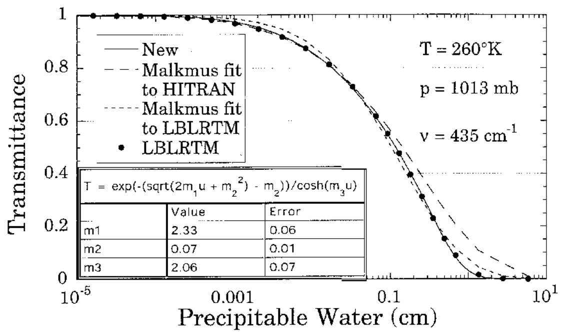

Figure 1. An example of the least squares fit of transmittances to LBLRTM calculations.

of 1013 mb and a temperature of 260 K. The dots in the figure represent the LBLRTM transmittances as a function of the precipitable water. The long-dashed line shows the band model results using the parameters derived under the weak and strong line limits. The short-dashed line represents the Malkmus transmittances calculated from the fitted model parameters. The solid line will be discussed in the next section. In the range of precipitable water from 0.1 to 10 cm, the differences in transmittances between band model and LBL model are reduced by about 5% to 10%. In general, the larger improvements appear where the absorber amount is larger and the absorption is stronger.

Figure 2 shows the RMS error of transmittances for water vapor line-only cases in 10 cm^{-1} bands over the entire long-wave region. The dots are calculated from the original Malkmus parameter formulations. The squares show the RMS errors calculated from the fitted model parameters. The diamond symbols will be discussed in the next section.

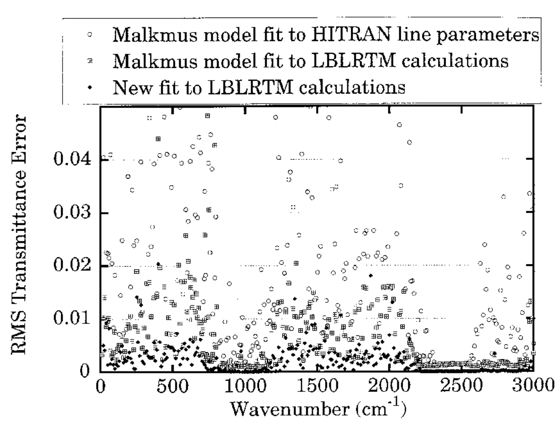

Figure 2. Spectral distribution of RMS transmittances differences between band models and LBLRTM.

The RMS errors of the transmittances calculated with Malkmus model parameters fitted to LBLRTM calculations are below 0.02 for most of the bands. The RMS errors are reduced more in the stronger absorbing regions. Since the RMS reflects the averaged error in the whole range of precipitable water, the error at one part can be larger than another. Indeed, when we improved the accuracy of calculated transmittances at larger absorber amount, we decreased the accuracy at lower absorber amount, as shown in Figure 1 by the short-dashed line. This method cannot be used in radiation models since it is selective on the atmospheric conditions. This indicates that there are many locations where the Malkmus model will not give accurate transmittances, despite the determination of the parameters from LBLRTM calculations.

New Model with Fitted Parameters

We have derived the following mathematical formula to express the distribution of transmittances as a function of the absorber amount:

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

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

Our representation of the transmittance is simply divide the Malkmus model by $\cosh(m_3\mu)$. This term's function is to increase the slope of transmittances with respect to precipitable water 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 temperature and pressure variation is modeled as follow, for the ith parameter,

$$m_i(T,p) = m_i(T_0,p_0)f_i(T)q_i(p) \qquad (3)$$

where

$$f_i(T) = \exp\left[a_i(T_0-T)+b_i(T_0-T)^2\right] \qquad (4)$$

$$q_i(p) = \sum_{k=0}^{k=4} c_{ki}[\log10(p)]^k \qquad (5)$$

The reference pressure and temperature are denoted as T_0 and p_0 respectively. The coefficients are determined for precipitable water range of 10^{-5} to 20 cm, pressure range of 1 - 1013 mb, temperature range of 220 to 300 K and spectral resolution of 10 cm^{-1} from 0 to 3000 cm^{-1}. The Curtis-Godson approximation is used to apply the homogeneous transmittances to the inhomogeneous atmosphere. Specifically, for the ith parameter,

$$\tilde{m}_i = \frac{\int m_i(T,p)du}{\int du} \qquad (6)$$

In the model calculation, the integrations over altitude and angle follow Ellingson.

As shown in Figure 1, the solid line depicts the improvement of the transmittance calculations by using the new formulation. The model calculations have much better agreement with LBLRTM for precipitable water of 0.1 - 10 cm. At the same time, the accuracy at the lower absorber amount is not sacrificed. The diamonds in Figure 2 show RMS errors calculated from the new model. The new form fits LBLRTM transmittances within 0.01 RMS for more than 97% of the spectral bands. The RMS errors are reduced more in the stronger water vapor absorption regions.

We have calculated the heating rate profiles due to water vapor line-only absorption for five McClatchey et al. (1972) standard atmospheres. Figure 3 shows the heating rates for Midlatitude Summer, Midlatitude Winter, Tropical, Subarctic Summer, and Subarctic Winter respectively. The solid lines are the LBLRTM heating rates, the long-dashed represent the calculations using parameters derived from the weak and strong line limits, and the dotted lines represent the results from the new model. The new results show particularly good agreement with LBLRTM in the summer cases and in the tropics, where both the precipitable water and temperature are higher.

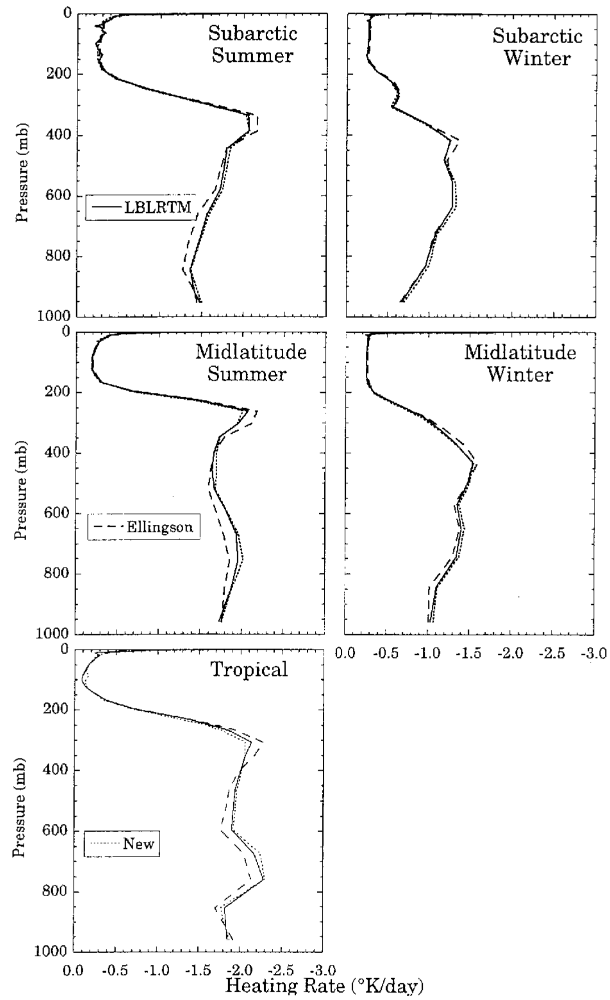

Figure 3. Heating rates calculated from water vapor line absorption only (no continuum) for McClatchey standard atmospheres.

Summary

The Malkmus model is insufficient to describe the dependence of water vapor transmittance on absorber amount in all spectral regions. A relatively simple modification of the Malkmus formulation allows fits to LBLRTM 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. Since the formulation of line transmittance follows directly from that used in LBLRTM, the addition of the CKD_2.1 water vapor continuum will follow the same manner used in LBLRTM, thereby allowing for a narrowband transmittance model with the same line-continuum consistency used in LBLRTM.

References

Clough, S.A., F.X. Kneizys and R.W. Davies, 1989: Line shape and the water vapor continuum. *Atmospheric Research*, **23**:229-241.

Clough, S.A., M.J. Iaconao, and J-1, Moncet, 1992: Line-by-line calculations of atmospheric fluxes and cooling rates: Application to water vapor. *J. Geopys. Res.*, **97**:15761-15785.

Ellingson, R.G., J. Ellis, and S. Fels, 1991: The intercomparison of radiation codes used in climate models: Longwave results. *J Geophys. Res.*, **96**:8929-8953.

Ellingson, R.G., S. Shen, and J. Warner, 1995: Calibration of radiation codes used in climate models: Comparison of clear-sky calculations with observations from the Spectral Radiation Experiment and the Atmospheric Radiation Measurement Program. In *Proceedings of the 4th ARM Science team Meeting*, CONF-940277, UC-402, U.S. Dept. Energy, Washington, D.C., 47-53.

Goody, R.M., 1964: *Atmospheric Radiation*, 436 pp., Oxford University Press, New York.

Lacis, A.A., V. Oinas, 1991: A description of the correlated k-distribution method for modeling nongray gaseous absorption, thermal emission, and multiple scattering in vertically inhomogeneous atmospheres. *J. Geophys. Res.*, **96**:9027-9063.

Malkmus, W., 1967: Random Lorentz band model with exponential-tailed S^{-1} line-intensity distribution function. *J. Opt. Soc. Am.*, **57**:323-329.

McClatchey, R.A., R.W. Fenn, J.E. Selby, F.E. Volz, and J.S. Garing, 1972: Optical properties of the atmosphere, In *Environ. Res. Pap. 411*, 3rd ed., 108pp., Air Force Cambridge Res. Lab., Bedford, Massachusetts.