A Study of Longwave Radiation Codes for Climate Studies: Validation with ARM Observations and Tests in General Circulation Models

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Introduction

One specific goal of the Atmospheric Radiation Measurement Program (ARM) is to improve the treatment of radiative transfer in general circulation models (GCM) under clear-sky, general overcast, and broken cloud conditions. We plan to contribute to this goal by attacking major problems connected with one of the dominant radiation components of the problem—longwave radiation. In particular, our long-term research goals are to

- develop an optimum longwave radiation model for use in GCMs that has been calibrated with state-of-the-art observations
- assess the impact of the longwave radiative forcing in a GCM
- determine the GCM's sensitivity to the radiative model used in it
- determine how the longwave radiative forcing contributes relatively when compared with shortwave radiative forcing, sensible heating, thermal advection, and expansion.

Our approach to developing the radiation model will be to test existing models in an iterative, predictive fashion. We will supply the Clouds and Radiative Testbed (CART) with a set of models to be compared with operationally observed data. The differences we find will lead to the development of new models to be tested with new data. Similarly, our GCM studies will use existing GCMs to study the radiation sensitivity problem. We anticipate that the outcome of this approach will provide both a better longwave radiative forcing algorithm and a better understanding of how longwave radiative forcing influences the equilibrium climate of the atmosphere.

Nature of Longwave Problems

Longwave radiation quantities—radiances, fluxes and heating rates—are usually calculated in GCM models as the cloud amount weighted average of the values for clear and homogeneous cloud conditions. For example, the downward flux at the surface, F, may be written as

$$F = (1 - N^*)\, F_o + N^* F_c$$

where F_o is the flux that would occur if the sky were clear with the observed, non-cloud radiative properties; F_c is the flux that would occur if the sky were completely covered by a single plane-parallel cloud layer of uniform optical properties; and N^* is the "effective" fraction of the sky covered by plane-parallel clouds.

The equation is deceptively simple, but there are significant problems associated with the calculation of F_o, F_c, and N^*. Our research program is directed at problems associated with each of the three terms. Nevertheless, we have focused our initial research on the clear-sky problem. Research on homogeneous and broken clouds problems will occupy more of our efforts during the next few years.

Clear-Sky Problems

In particular, we are interested in answering the following questions:

- How well do the models reproduce observed radiances for clear-sky, low aerosol conditions?
- Which continuum formulations give the best agreement with observations?
- How well do simple, empirical aerosol models work on a routine basis?
- How do model uncertainties in downwelling radiance at the surface translate into uncertainties in the vertical profiles of upward and downward fluxes and heating rates?

Our approach to answering these questions is to

- test the accuracy of representative examples of various model types for calculating the spectrally integrated radiance over relatively broad intervals of the order of 20 cm^{-1} or greater
- use identical meteorological data in each model
- use identical numerical techniques, where possible, to perform the various calculations.

The approach requires the simultaneous measurement of the radiative properties of the atmosphere and the vertically downward spectral radiance. The observational requirements depend on the individual problems to be studied, but the list is quite long.

Sensitivity Studies

In anticipation of the measurements, we have begun a study of the sensitivity of calculations of the vertically downwelling radiance calculations at the surface to possible errors in the measurement of the radiatively important variables for clear-sky conditions (i.e., temperature, H_2O, O_3, CO_2, N_2O, CH_4). In particular, we have used the Air Force Geophysical Laboratory (AFGL) Mid-latitude Summer atmospheric profile and several different radiation codes to determine the sensitivity of calculations to

- different formulations of the water vapor continuum
- systematic and random errors in H_2O, T, tropospheric O_3, and stratospheric O_3
- systematic increases in the concentrations of CO_2, CH_4 and N_2O
- aerosol loadings.

Some of the results of the sensitivity calculations are shown in Figures 1 through 9. Overall, the results show the following:

- At near sea level conditions, major useful research is possible only in the 500 to 1400 cm^{-1} region.
- Systematic errors in the measurement of water vapor, temperature, and aerosols pose the greatest risk for validation of the models to better than 5% in these regions.
- Separation of the various continuum formulations requires the specification of the vertical distribution of temperature and water vapor in the lowest 4 km to within about 1 K and 5%, respectively.

There are many other results that could not be shown in this summary paper. However, we will be happy to provide interested individuals with copies in GIF format which can be displayed by most desktop computers.

Homogeneous Cloud Problems

Our research is directed at answering the question: How well do existing, generic, bulk parameterizations of cloud radiative properties allow the calculation of downwelling radiance at the surface? The observations we require include cloud base altitude, liquid water content, and the radiative properties of the clear-column below the cloud base. We are performing the required sensitivity calculations at this time, and hope to present results on this aspect of the study at the next meeting of the Science Team.

Broken Cloud Study

Since liquid-water clouds are nearly black in the infrared, cloud geometry dominates the longwave broken cloud problem. Our research is directed at testing the accuracy of parameterizations of N^* in terms of bulk geometric factors such as the absolute cloud amount N, aspect ratio α, thickness H, spacing d, and the distribution of clouds on the horizontal plane υ. However, a number of difficulties are associated with research on this problem:

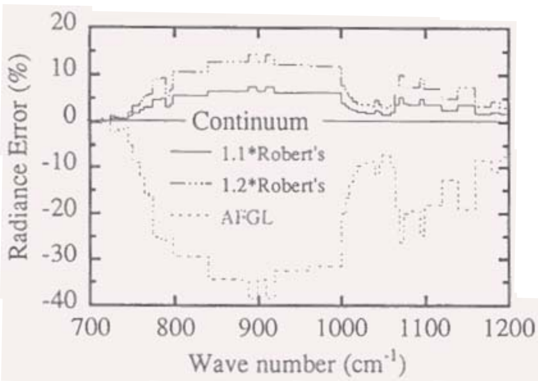

Figure 1. Effects of different water vapor continuum formulations on the downwelling radiance at the Earth's surface as calculated by Ellingson's narrow band model.

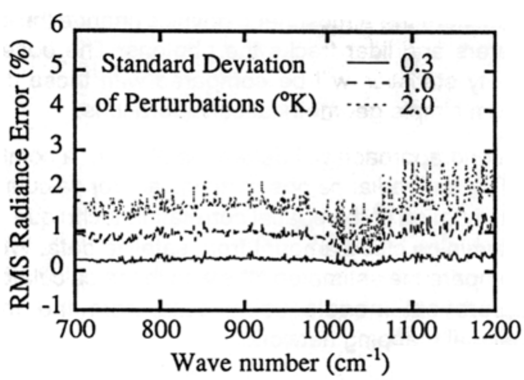

Figure 2. Effects of random temperature perturbations on the downwelling radiance at the Earth's surface as calculated by FASCODE3.

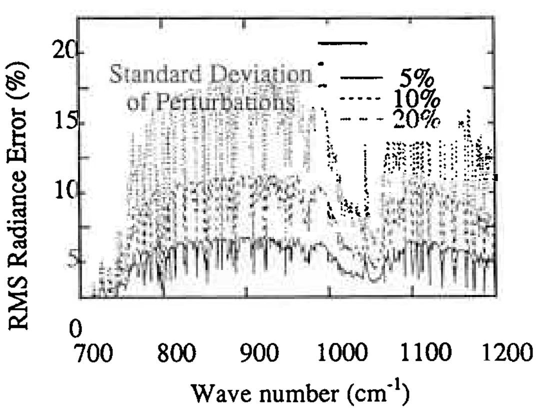

Figure 3. As in Figure 2, but for relative humidity.

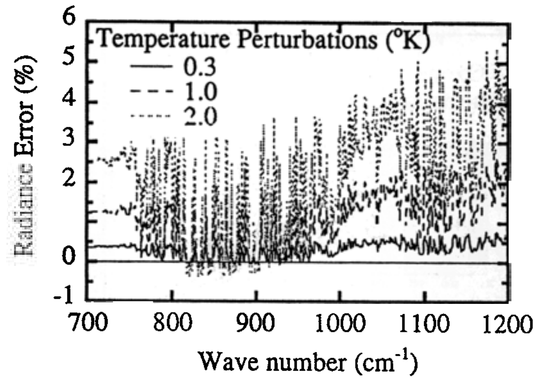

Figure 4. As in Figure 2, but for systematic temperature increases.

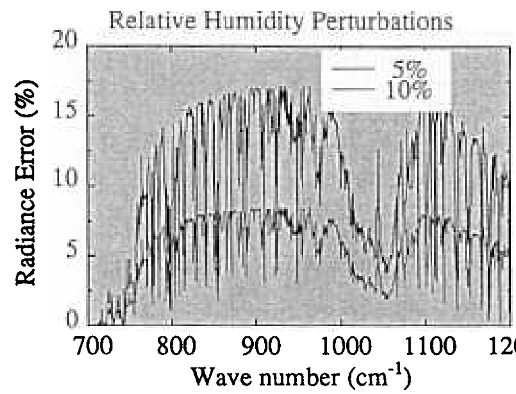

Figure 5. As in Figure 3, but with systematic relative humidity increases.

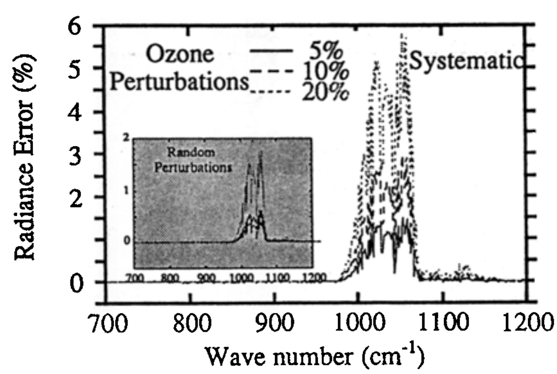

Figure 6. Effects of systematic and random tropospheric ozone perturbations on FASCODE downwelling radiance calculations at the Earth's surface.

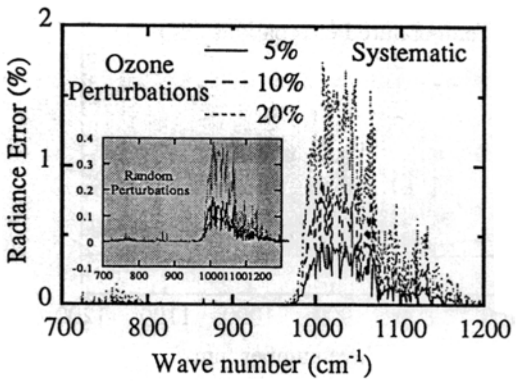

Figure 7. As in Figure 6, but for stratospheric ozone perturbations.

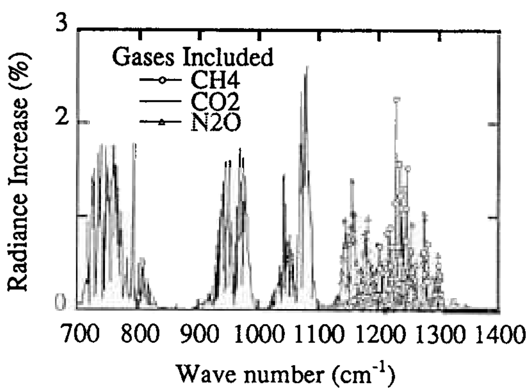

Figure 8. Effects of 10% increases in trace gas concentrations on downwelling radiance at the Earth's surface.

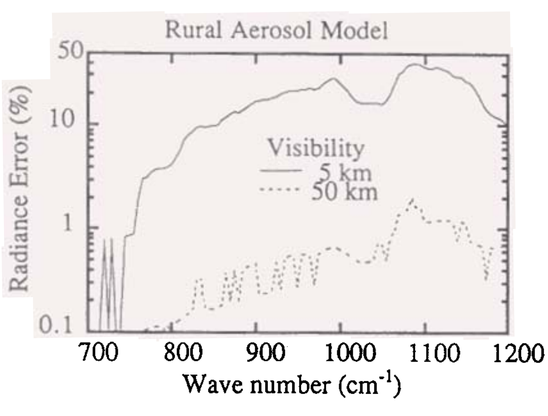

Figure 9. Effects of different aerosols on LOWTRAN7 calculations of the downwelling radi-ance at the Earth's surface.

- Finite size cloud effects on F_o at the surface are generally within the 5% accuracy of the flux observations.
- There are no standard methods for estimating the required cloud properties.

We are evaluating two different approaches to testing models of partial cloudiness, both of which rely on relatively on elementary physics. That is, if clouds were black and randomly distributed, the quantities necessary to perform the radiation calculations are the probability of a clear line of sight through the atmosphere at all angles and the probability of seeing a cloud between given altitude regions at all angles. The major difficulty is the determination of the probability functions.

The first approach is to use scanning lidars and cloud imagery to develop empirical probability statistics. This is similar to performing Monte Carlo simulations on a computer, but here the atmospheric physics change the cloud parameters and lidar tracks the photons. The observed probability statistics will be compared with those calculated from simple geometrical considerations.

The second approach will determine N* from a combination of flux and radiance observations and/or calculations using a variation of the spatial correlation technique used for determining cloud amount from satellite data. We will then compare the estimated N*'s with those calculated by the theoretical models using data from the three-dimensional mapping network.

General Circulation Model Testing

It is already clearly evident that longwave radiation effects can have a pronounced impact on climate model performance and that changes in chemical constituents as well as clouds in a prediction model can yield forecasts which, if accurate and based upon careful observations, could cause serious societal concern. Numerous factors play a role in the overall thermal forcing of a climate model; and while we know that greater accuracy from a longwave radiation model will improve our skill in climate prediction, we must also establish a more reliable estimate of the relative importance of longwave radiative forcing in a climate model in comparison to its other features.

Since the radiative model depends on moisture, cloud, temperature, surface energy budget, and parameterization of sub-grid scale effects, we must ultimately identify the impact of the forcing on all these parameters. However, in the initial stages of this study, we will strive to establish the sensitivity of climate modeling on the quality of the radiative model alone. The numerical experiments we plan to carry out should provide us with the information needed to answer some of these sensitivity questions.

We anticipate that the outcome of this experiment will provide us with both a better longwave radiative forcing algorithm and a better understanding of how longwave radiative forcing influences the equilibrium climate of the atmosphere. As our experiments proceed, it seems reasonable that the other forcing functions and, in particular, shortwave radiative forcing could be studied in a corresponding way. We would be pleased to collaborate with other specialists who have an interest in understanding the properties of these functions.

There are many details associated with this study which obviously cannot be discussed in this short summary paper. However, we will be happy to discuss them at length with members of the Science Team.