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

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Introduction

Research by the U.S. Department of Energy (DOE) has shown that cloud radiative feedback is the single most important effect determining the magnitude of possible climatic responses to human activity. However, these effects are still not known at the levels needed for climate prediction. Consequently, DOE has launched a major initiative - the Atmospheric Radiation Measurements (ARM) Program - directed at improving the parameterization of the physics governing cloud and radiative processes in general circulation models (GCM's).

One specific goal of ARM is to improve the treatment of radiative transfer in GCM's under clear-sky, general overcast and broken cloud conditions. In 1990, we proposed 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 GCM's that has been calibrated with state-of-the-art observations,
- assess the impact of the longwave radiative forcing in a GCM,
- determine the sensitivity of a GCM to the radiative model used in it, and
- determine how the longwave radiative forcing contributes relatively when compared to 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 GCM's 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.

This report summarizes the activities of our group during the project's second year to meet our stated objectives. The report follows the original proposal in dividing the discussion into sections on Radiation Model, General Circulation Model Testing, and Science Team Activities.

Radiation Model Testing Activities

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

$$F = (1 - N^*) F_0 + N^* F_c$$

where F_0 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. However, the focus of the first 18 months of the project has been on the clear-sky problem. Nevertheless, we have begun to devote more attention to the homogeneous and broken clouds problems during the past six months as is described below.

Clear-sky Study

There are many questions concerning the accuracy of the observing systems and the sensitivity of the models to input data errors that must be answered before the start of the ARM observations. We began to study some of these early in 1990 as part of another DOE sponsored project (ICRCCM Phase II: Verification and Calibration of Radiation Codes in Climate Models), and we have expanded our activities to cover the variety of models discussed in the original proposal with the conditions expected at the various ARM sites. The questions being studied include:

- To what level of accuracy will we be able to test the models given the measurement uncertainties in the radiometric quantities and the atmospheric radiative properties?
- Given common numerical techniques and identical meteorological and spectral data, which models can be expected to be show differences greater than this level of accuracy?
- Given different sets of spectral data and parameterizations, will the uncertainties in the observations allow us to distinguish between the different models? That is, for standard meteorological data sets, what are the expected magnitudes of disagreement?
- How will multiple scattering by clouds influence interpretation of clear and cloudy column radiances?
- How will varying amounts of aerosol complicate the interpretation of comparisons between observed and calculated radiances and fluxes?

In anticipation of measurements of downwelling longwave radiance at the first ARM site, we have been studying the sensitivity of calculations 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 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, and
- aerosol loadings

Many of the results of the sensitivity calculations are shown in Figures 1 through 9 of Ellingson and Baer's ARM Science Team report, which will soon be available from PNL. Overall, the results show:

- 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.

In addition to the testing of the sensitivity of the models, we began the preparations for operational testing of a variety of models with observations. The suite of models include several used in GCM's (including GLA, CCM1, AES, NMC and ECMWF) and several detailed models (e.g., AFGL's MODTRAN and LOWTRAN 7, and Ellingson's narrow band models). We have modified several of the GCM-type models to calculate radiance, rather than flux, so that the models can be compared with spectrally integrated observations from the interferometer. We expect the models to be ready for testing with observations, at least for clear-sky conditions, by about May 1, 1992.

Cloudy-Sky Studies

a. Homogeneous Cloud Cover

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 in the process of performing the required sensitivity calculations at this time, and hope to complete our analysis during the next six months.

b. Partial Cloud Cover

Since liquid-water clouds are nearly black in the infrared, cloud geometry dominates the longwave broken cloud problem. Our research in this area 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 γ. However, there are a number of difficulties associated with research on this problem, including:

- Finite size cloud effects on F_0 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 in the process of 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.

A recent addition to our group, Dr. Rosemary Killen, has been developing techniques for incorporating the effects of the geometric properties of fractal clouds on longwave radiative transfer. As of this report, we have succeeded in obtaining an analytic expression for N* for randomly distributed clouds with uniform fractal dimension, and we have compared calculations obtained from it with results from randomly distributed cylinders. Our preliminary results show that, unlike the random distribution of cylinders, the results with fractals are sensitive to the mean cloud spacing as well as to the aspect ratio.

We have recently begun testing the sensitivity of the downward flux at the surface to uncertainties in parameters used in different techniques for estimating the effects of partial cloud cover. Pending the completion of the model for fractal cloud dimensions, our study is focusing on the use of models of random distributions of flat, cuboidal and cylindrical clouds. This analysis is a necessary first step to allow us to proceed with the development of techniques for testing models of partial cloudiness with observations.

General Circulation Model Testing

As described in the original proposal, the purpose of this part of the study is to:

- assess the impact of the longwave radiative forcing in a climate model (GCM),
- determine the sensitivity of such a model to the radiative model used in it, and
- determine how the longwave radiative forcing contributes relatively when compared to shortwave radiative forcing, sensible heating, thermal advection and expansion.

Our investigations into model impacts from radiative forcing and ultimately the response of climate prediction have proceeded along two lines, lines which will ultimately converge. In the first, we study the single column models to identify the sensitivity and how model improvement will assist in improved prediction. In the second line we investigate three dimensional distributions of heating from column models in large scale models and assess the scale sensitivity of this forcing.

Single Column Model Investigations

We now have available for study six different column models which we can test at our discretion. We consider the effects of vertical resolution and level placement, regional and seasonal data sources, and inclusion or lack thereof of clouds. The models we currently test are:

CSU/Randall
NCAR/CCM
UMCP/Ellingson
AES/Garand
NMC/GFDL
ECMWF/Blanchet

These models have provided heating rates based on the now classical McClatchey Soundings as well as others over the oceans and high/rough topography. In addition, we have tested the models for various vertical distributions. We have used a standard set of 33 levels. We have then reduced this set to twelve levels to correspond to those used in the NCAR/CCM. Those twelve levels were then readjusted to give a distribution which could be considered optimum under specific conditions. The heating rates for these experiments were generated without clouds to give a reference.

The results from the calculations indicate that significant differences among the models show up in the upper levels of the stratosphere. The placement of levels makes some difference in the heating rates but the high resolution does not necessarily make the models yield more similar results. Since differences show up on the order of several degrees per day, it is important that we have a quality data base against which to test these results. We must know what the correct heating rates are and how we might adjust the column models to optimize their output.

The experiments with the available models are now being repeated with clouds. Additionally we will test for a greater variety of soundings to set the bounds on the range of output the column models can produce.

Global Model Heating Distributions

While studying the single column models, we have begun to diagnose the multi dimensional distribution of heating rates due to longwave radiation algorithms, shortwave heating rates and convection. We have available data sets from both the NCAR CCMI and the NMC global model. Since the heating rates are calculated periodically during an integration and are archived on the three-dimensional grid, we can select from the archive tapes and analyze the results. We are currently studying one time record from a CCMI annual cycle calculation. We have projected the heating rates for both the longwave and the short wave algorithms onto their spectral wave components at each of the model levels and for truncations at both R15 and T42. Several observations are significant. At all model levels, the longwave heating is substantially longer than the shortwave heating, often by as much as an order of magnitude. This suggests that model improvement in the single column models for longwave effects will have a substantially larger impact on forecasts that corrections to the shortwave algorithms. An additional observation which might have critical impact on climate predictability is the significant heating rates associated with the long wave heating at shorter scales. Since the short scales transfer their energy to the subgrid scales rapidly, this result will have a pronounced impact in both the appropriate truncation point for a model, and how the subgrid scale processes are parameterized.

We are analyzing similar data sets for the NMC model, a model which has different algorithms than the NCAR model and which has more resolution. We will compare the observations of the NMC model with those discussed above from the NCAR model when the data analysis is completed. For the NMC model, we will also assess the relative effect on heating of convection, since those fields are readily available to us.

Science Team Activities

During the past year, Professors Ellingson and Baer have participated in several meetings of ARM Science Team (AST) working groups as well as the annual AST meeting. Ellingson has been selected to the Executive Committee of the ARM Science Team and will represent the Instantaneous Radiative Flux working group. Furthermore, Ellingson assisted with the ARM Implementation Review at Pacific Northwest Laboratories during April 1991 with an inspection of the first ARM site in March 1992

Overall, our project and ARM have benefitted from these meetings through the identification of research groups with similar interests and through the development of ideas for successful field and numerical experiments.

Summary

Overall, the project is proceeding much as had been anticipated in the original proposal. The most noteworthy accomplishments to date include:

- the completion of the sensitivity analyses of the radiation model calculations for the effects of uncertainties in the measurement of water vapor, temperature and trace gases for mid-latitude conditions,
- the derivation of an analytic expression for N* for randomly distributed clouds with fractal dimension
- the acquisition and initial testing of a variety of GCM radiation codes
- the observation of significant heating rates associated with longwave radiation at shorter horizontal scales., and
- the continuing development of scientific comraderie with several members of the ARM Science Team.

We anticipate the project to continue during the next year as originally planned. The next year should witness our first significant results from comparisons of observations with calculations.

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