Analysis of Cloud Radiative Forcing and Feedback in a Climate General Circulation Model

A. Lacis
NASA Goddard Space Flight Center
Institute for Space Studies
New York, NY 10025

Objectives

The overall objectives of the Atmospheric Radiation Measurement (ARM) program research at the Goddard Institute for Space Studies (GISS) are to refine and validate the GISS General Circulation Model (GCM) radiation code through model intercomparisons and comparison with ARM observations, to refine and restructure the GISS GCM diagnostics to facilitate more informative comparisons with global radiation/cloud data sets, and to use ARM data to develop improved parameterizations of the radiative impact of clouds and to study the interaction of dynamics and radiation.

Task 1: Improvement of GISS GCM Radiative Codes

Subtask 1a: Improvement of Solar Radiative Code

The key component of this subtask is the development of a particle-size-dependent multiple scattering algorithm. Our proposed approach for development of this multiple scattering parameterization anticipated using van de Hulst's similarity relations, which are quite accurate for representing solar zenith angle integrated (spherical) albedos for different optical thicknesses and for different particle size distributions.

We found, however, that the simple scaling with similarity relations that is applicable with good accuracy for spherical albedos, is not readily transferrable to plane albedos without introducing complex compensating parameterizations. Accordingly, we adopted a more direct approach using a 4-dimensional interpolation of cloud radiative properties, i.e., the interpolation of cloud albedo and diffuse transmission as a function of solar zenith angle, optical depth, cloud particle size, and single scattering albedo. These results will replace the current approach which uses the "Single Gauss Point" doubling algorithm to obtain cloud radiative properties. However, the stack of homogeneous layers that make up the atmospheric column will be "added" using the Single Gauss Point adding algorithm with the "extra angle" formulation used to model the solar zenith angle dependence. The interpolation tables are being constructed to reproduce the Mie scattering results for liquid water cloud properties, with the asymmetry parameter serving as the index for interpolating the extinction cross-section dependence on wavelength and on particle size.

In addition to providing the capability to model the radiative effects of changing cloud particle size, this new approach for modeling multiple scattering should also improve the accuracy of the radiative transfer modeling as well as improve the computational speed of the GCM solar radiation code. This improvement to the solar radiation code is a critical component in our effort to evaluate our improved cloud prediction scheme properly (Task 3). Once the liquid cloud particle parameterization is in place, we will extend the treatment to include ice clouds.

Subtask 1b: Improvement of Longwave Radiative Code

A key element of this subtask is the improvement of the water vapor continuum formulation in the GCM longwave radiative code. Based on an intercomparison of GCM radiative cooling rates (GISS, NCAR, GFDL) against line-by-line results (Fels et al. 1991), we find that the GISS GCM cooling rates are in generally good agreement with the line-by-line calculations. However, there are some unexplained differences.

One source of error that we have identified can be attributed to our use of the Roberts et al. (1976) water vapor continuum formulation. Recent measurements suggest that the Roberts et al. (1976) continuum may overestimate the continuum opacity by 25%.

To evaluate the climatic significance of the different continuum absorption formulations, we are proceeding to replace the Roberts et al. (1976) continuum with newer formulations. Additional GCM and line-by-line comparisons are also being initiated to more clearly identify other sources of error. Toward this end, future measurements obtained during Cloud and Radiation Testbed (CART) and First ISCCP Regional Experiment will be invaluable. Until these data become available, we will use High Resolution Interferometer Sounder (HIS) aircraft measurements for our line-by-line data versus model comparisons. The effects of multiple scattering on thermal radiation are generally small, and thus usually ignored. As a by-product of parameterizations developed in Subtask 1a, we will have a multiple scattering model that can also be applied for longwave calculations. We will use these results to examine the accuracy of the parameterized correction for multiple scattering effects that is currently being used in the GISS GCM longwave calculations.

Subtask 1c: Improvement of Water Vapor Continuum Formulation

Accurate knowledge of water vapor continuum absorption is very important for climate modeling applications. However, laboratory measurement of the continuum absorption for pressure and temperature conditions of interest is difficult because of condensation effects and the long pathlengths required.

The full theoretical understanding and the ability to model the continuum absorption theoretically have also proved difficult and elusive in the past. Nevertheless, through fortunate circumstances, Dr. Q. Ma, who has become a recent member of our ARM team, has developed a comprehensive theoretical formalism to calculate the continuum absorption over a wide range of frequency and temperature.

The theory is based on the quasistatic approximation for the far wing limit and the binary collision approximation of one absorber molecule and one bath molecule. In line space, the motion of the dipole moment of the absorber molecule is approximately expressed as the ordered product of the two time displacement Liouville operators, one related to the intermolecular potential and the other to the unperturbed Hamiltonian. The calculations are made assuming an interaction potential consisting of an isotropic Lennard-Jones part with two parameters obtained from the virial data and the anisotropic dipole-dipole part, together with measured line strengths and positions of allowed transitions. The results are in good agreement with available measurements and provide a theoretical basis for the temperature and wavelength dependence of the continuum absorption beyond the range available from laboratory measurements.

Further theoretical analyses are needed to improve our understanding of the theoretical foundation and sensitivity to physical parameters and approximations used in computing the continuum absorption. Likewise atmospheric measurements to verify the accuracy of the wavelength and temperature dependence of the continuum absorption will be pursued as part of the ARM CART radiation measurements program.

Subtask 1d: Improvement of Line-By-Line Radiative Code

We are developing a comprehensive radiative model to compute line-by-line gaseous absorption in a vertically nonhomogeneous multiple scattering atmosphere using the doubling and adding method. This model will serve as a benchmark for assessing the accuracy of the GCM radiation code and other radiation models that are being used at GISS for climate studies. The line-by-line model will also serve as our principal interface for comparing and validating radiation calculations with detailed radiative measurements that will be obtained as part of our participation in the ARM CART program to refine and validate the GISS GCM radiation code.

Pending the availability of ARM measurements, we are currently making comparisons with available HIS aircraft and IRIS spacecraft measurements. We have completed a set of preliminary calculations using this model to compute radiances in the thermal window region to retrieve sample cirrus cloud properties such as optical depth, effective particle size, and cloud-top temperature. The absence of significant line absorption in the thermal window region above typical cirrus altitudes permits accurate cloud property retrievals without line absorption complications. The gaseous absorbers included in the model thus far are H_2O, CO_2, O_3, CH_4, and N_2O. To improve the line-by-line model accuracy for CO_2, we are including corrections for Q-branch line coupling. We are also including the new water vapor continuum formulation in the line-by-line model. Since the formalism for combining line absorption with continuum absorption is different for the new continuum formulation than that used in FASCODE3, it will be essential to make detailed intercomparisons between the two line-by-line models.

Task 2: Improvement of GISS GCM Model Diagnostics

Subtask 2a: Improvement of GCM Diagnostics

The process of restructuring the GCM-generated on-line diagnostics continues. We have thus far rewritten parts of the GCM diagnostics package to facilitate GCM intercomparisons that have been conducted by R. D. Cess. The most recent of these intercomparisons is the study of snow-climate feedback among 17 general circulation climate models. For this experiment, the GCM simulations were conducted for steady-state April conditions for +2 K and -2 K perturbations. The results demonstrate that, in addition to the conventional expectation of a warmer Earth producing less snow cover, the snow feedback can incorporate additional amplifying or moderating mechanisms caused by cloud and longwave radiation interactions, with the net effect that snow/ice albedo feedback was found to differ significantly among the 17 GCMs compared. The basic results of this intercomparison are published in *Science*.

Subtask 2b: Improvement of Off-Line One-Dimensional Modeling Diagnostics

The off-line one-dimensional radiative-convective-dynamic equilibrium model to analyze GCM feedbacks is basically completed. As a test case of the feedback analysis model, we have analyzed model feedbacks from several GCM experiments that were part of a volcanic aerosol climate forcing study. Besides the globally uniform volcanic aerosol forcing, we examined the results from 2X CO_2 and ice age (18 K) simulations. In all cases, atmospheric water vapor was found to be the principal positive feedback. Snow/ice albedo was a strong positive feedback at high latitudes, with land ice feedback prominent only in the 18 K run. However, cloud and dynamic energy transport feedbacks showed significant latitudinal changes and interactions for the different types of climate forcing applied. A description of the feedback analyses of this study has been submitted to *J. Climate*.

Subtask 2c: Intercomparison of GCM Results with Earth Radiation Budget Experiment (ERBE) and International Satellite Cloud Climatology Project (ISCCP) Data

This is a key element in assessing the ability of the GCM to simulate current climate. Intercomparisons of GCM results with ERBE and ISCCP satellite measurements will be diagnostic of both the radiative and cloud prediction parameterizations that we are currently developing to upgrade the GCM performance. Accordingly, implementation of this subtask is deferred until the radiative and cloud parameterizations are in place.

Task 3: Improve the Treatment of Clouds in the GISS GCM

We have tested an improved cumulus and stratiform cloud parameterization in the GISS GCM. The new cloud parameterization includes a mass flux computation designed to produce a quasi-equilibrium between convective-scale and large-scale motions; it provides for simultaneous deep and shallow convection, transport by cumulus-scale downdrafts, as well as environmental subsidence. Stratiform clouds in the new parameterization are based on a cloud liquid/ice water budget, including a representation of mesoscale cumulus anvils, different microphysical properties for liquid and ice, collection of cloud water by precipitation, diffusional growth of ice, cloud-top entrainment instability, and variable optical thickness. A fully interactive GCM simulation with cloud particle size dependent multiple scattering calculations is not yet possible, but the test simulations conducted thus far are sufficient to evaluate the impact of the new cloud parameterization on atmospheric dynamics including the vertical transport of atmospheric water vapor. The results show enhanced upward moisture transport by the general circulation and increased injection of water vapor and ice at the cumulus cloud top level. This produces a strong positive feedback due to water vapor. The model behavior is consistent with several satellite estimates of water vapor feedback and does not produce the hypothesized drying of the upper atmosphere as suggested by Lindzen (1990). The results of this study are published in *Nature*. Additional GCM tests using the new cloud parameterization scheme are in progress.

Publications

The following publications listed below have been supported in whole or in part by funding provided by the U.S. Department of Energy through an Interagency Agreement under the Atmospheric Radiation Measurement Program.

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