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

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The principal objectives of the Atmospheric Radiation Measurement (ARM) Program research at the Goddard Institute for Space Studies (GISS) are 1) to improve and validate the radiation parameterizations in the GISS general circulation model (GCM) through model intercomparisons with line-by-line calculations and through comparisons with ARM observations, 2) to improve the GCM diagnostic output to enable more effective comparisons to global cloud/radiation data sets, and 3) to use ARM Cloud and Radiation Testbed (CART) data to develop improved parameterization of clouds in the GCM and to study the interaction of dynamics and radiation.

Improvement of GCM Radiation

We have tested and evaluated several different approaches for modeling particle-size-dependent multiple scattering in the GISS GCM shortwave algorithm. These involve modifications to the current Single Gauss Point (SGP) doubling-adding algorithm that is used to calculate cloud and aerosol radiative properties. We have explored the use of two- and three-dimensional interpolation schemes in the radiative input parameters to the SGP doubling algorithm. These schemes have been least-squares fitted to reproduce accurately the reflected and absorbed radiation for small and large optical thicknesses and for particle sizes characteristic of clouds and aerosols. In addition, they have been fitted to reproduce the albedo dependence on solar zenith angle. We have also explored using a four-dimensional interpolation scheme of cloud albedos as a function of solar zenith angle, optical depth, cloud particle size, and single scattering albedo. Each approach has different advantages and limitations in precision, speed, or storage requirements that need to be weighed and optimized. Upgrading the current GCM treatment of multiple scattering is needed to fully implement the interactive cloud prediction scheme that we have been developing for the GISS GCM. More flexibility is also required to enable handling of particle-size-dependent scattering effects to accommodate the different types of aerosols being included in the GCM simulations.

For the longwave calculations, cloud particle size dependence has been included by mapping the spectral dependence of the cloud absorption cross-sections (obtained from Mie scattering calculations) into the 25 spectrally non-contiguous k-distribution intervals used for gaseous absorbers. The resulting cloud absorption coefficients are then tabulated and interpolated as functions of particle size. A corresponding table of emissivity correction factors is also generated as part of the longwave algorithm to correct the outgoing radiation at cloud-top level for multiple scattering effects that impart a finite reflectivity to clouds at thermal wavelengths. A similar set of absorption cross-section tables is also being generated to model the radiative effects of aerosols at thermal wavelengths.

The theoretical formulation for the continuum absorption by water vapor is one of the major accomplishments of our ARM Program participation. Based on the quasistatic approximation for far-wing absorption, and the binary collision approximation of one absorber molecule and one "bath" molecule, the continuum absorption was numerically calculated using an interaction potential consisting of an isotropic Lennard-Jones part and anisotropic dipole-dipole part, together with the measured line strengths and positions of allowed transitions. The basic results obtained to date were summarized in the ARM Program Poster Session at the American Meteorological Society meeting in Anaheim, California (Ma and Tipping 1993).

The theoretical formalism is applicable over the full range of frequencies and temperatures encountered in the atmosphere and has been compared and validated against available observational data. The continuum results are important not only for providing a theoretical model for the water vapor continuum absorption as a function of wavelength and temperature, but also for improving our basic understanding of the physical mechanism of continuum absorption and of spectral line-shape and far-wing absorption.

We have incorporated the Ma and Tipping formulation of continuum absorption into our multiple scattering line-by-line model and have used this model to compare synthetic spectra against the Nimbus-4 IRIS measurements. We have been testing the performance of our line-by-line model against this high spectral resolution Fourier transform infrared (FTIR) satellite data in preparation for the ARM Cloud and Radiation Testbed (CART) Atmospheric Emitted Radiance Interferometer (AERI) and AERI-X measurements.

We have demonstrated the feasibility of using this line-by-line model to retrieve cloud information such as optical depth, effective particle size, and cloud-top temperature from IR spectra. The absence of significant line absorption in the thermal window region above typical cirrus altitudes permits accurate cloud property retrievals with minimum complications from line absorption. The ultimate goal is to validate the performance of the GCM radiation code through intercomparisons with line-by-line calculations. Thus, the line-by-line model serves to bridge the gap between the GCM radiation model and observational data.

Improvement of GCM Diagnostics

We have rewritten parts of the GCM diagnostics package to facilitate GCM intercomparisons. This includes extracting from the GCM output cloud radiative forcing components in Method II and Method III formats to enable more accurate intercomparisons with other GCM results and with observational data from the International Satellite Cloud Climatology Project (ISCCP) and the Earth Radiation Budget Experiment (ERBE). We have also developed a two-dimensional radiative-convective-advective equilibrium model (2-D RCAM) to analyze the latitudinal dependence of GCM feedbacks (Lacis and Sato 1993).

In the 2-D RCAM analysis, zonally averaged annual mean GCM climatological information for 1.02 S_0 and doubled CO_2 experiments were used to determine the latitudinal dependence of feedback sensitivity. Although the applied radiative forcing was very different in the two experiments, the latitudinal dependence of the GCM surface temperature response and of the feedback sensitivity was remarkably similar. In both cases, atmospheric water vapor was the principal positive feedback, and snow/ice albedo was a strong positive feedback at high latitudes. Clouds were a positive feedback at low to middle latitudes, but produced negative feedback in the polar regions. Advected energy feedbacks showed significant latitudinal changes with substantial cancellation of cloud feedback contributions.

We also made intercomparisons of several satellite data sets (ISCCP, Nimbus-7, ERBE) for data diagnostic purposes and for comparison to GCM results. An empirical orthogonal function (EOF) analysis of high clouds in the ISCCP and Nimbus-7 data sets showed similar variability in magnitude, phase, and global distribution between the two data sets (Cairns 1993). Thus, both data sets provide effective high cloud validations and were particularly useful in diagnosing the El Niño-Southern Oscillation (ENSO) high-cloud signature in GCM simulations. EOF analysis was also instrumental in detecting calibration and data artifacts that can impact the variability of cloud diurnal and seasonal cycles (Carlson and Wolf 1993). It was very clear from this analysis that clouds undergo complex diurnal and seasonal amplitude and phase changes and that these variations provide powerful diagnostic tests of both the radiative and cloud prediction parameterizations that are being developed to upgrade the GCM performance.

Improvement of GCM Cloud Treatment

We have test-run an improved cumulus and stratiform cloud parameterization in the GISS GCM (Del Genio et al. 1993). 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.

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, producing a strong positive feedback due to water vapor. Also, the new cloud scheme was able to reproduce the El Niño high-cloud signature in an Atmospheric Model Intercomparison Project (AMIP) simulation, while the old scheme could not.

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