Analysis of Cloud Radiative Forcing and Feedback in a Climate GCM

Final Report for

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ACCOMPLISHMENTS UNDER PREVIOUS SUPPORT

The principal objectives of the research supported at the Goddard Institute for Space Studies (GISS) by the Atmospheric Radiation Measurement (ARM) Program for a three year period commencing September, 1990, were: (1) to improve and validate the radiation parameterizations in the GISS GCM through model intercomparisons with line-by-line calculations and through comparisons with ARM observations, (2) to improve the GISS GCM diagnostic output to enable more effective comparisons to global cloud/radiation data sets, and (3) to use ARM data to develop improved parameterization of clouds in the GCM and to study the interaction of dynamics and radiation.

The ARM Program support has made it possible to establish and support an active and productive research group at GISS specializing in radiative transfer and cloud process modeling in support of improving the performance of a climate GCM.

Improvement of GCM Radiation Codes

We have tested and evaluated several different approaches for including particle size dependent multiple scattering in the GISS GCM shortwave algorithm. These include modifications to the current Single Gauss Point (SGP) doubling algorithm that is used to calculate cloud and aerosol radiative properties in individual GCM layers, and utilizing a 4-dimensional interpolation scheme of cloud albedos as a function of solar zenith angle, optical depth, cloud particle size, and single scattering albedo. The SGP adding algorithm with the "extra angle" formulation to model the solar zenith angle dependence is then used to add the stack of layers comprising the atmospheric column. Upgrading of the present GCM treatment of multiple scattering is needed to fully implement the interactive cloud prediction scheme (Del Genio *et al.*, 1993) that we have been developing for the GISS GCM. More flexibility in handling of particle size dependent scattering effects is also needed to accommodate the different types of aerosols that are being included in the GCM simulations.

Cloud particle size dependence in the GCM longwave calculations 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 that are used for gaseous absorbers. The resulting cloud absorption coefficients are then tabulated and interpolated as functions of particle size. A corresponding table emissivity correction factors is also included to correct the outgoing radiation at cloud-top level for multiple scattering effects which impart a finite reflectivity to clouds at thermal wavelengths. A similar set of absorption cross-section tables in also being generated to model the radiative effects of aerosols at thermal wavelengths.

Recently, a theoretical foundation has been developed for calculating the water vapor continuum absorption. The basic results to date are summarized in Ma and Tipping (1993). The theoretical formalism is applicable over a broad range of frequency and temperature and has been compared and validated against available observational data. The continuum results are important not only for providing 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 line-shape and far-wing spectral dependence of water vapor absorption.

The Ma and Tipping formulation of continuum absorption is being incorporated into the GCM radiation code and also into our multiple scattering line-by-line model. Since validation of the GCM radiation code against observational data is more easily accomplished through model intercomparisons with more detailed radiation calculations, the line-by-line model serves as the bridge between GCM radiation modeling and observational verification.

We have been testing the performance of our line-by-line model using Nimbus-4 IRIS data in preparation for analysis of the ARM AERI and AERI-X measurements. We have demonstrated the feasibility of using this model to retrieve cloud information such as optical depth, effective particle size, and cloud-top temperature. In particular, the absence of significant line absorption in the thermal window region above typical cirrus altitudes permits accurate cloud property retrievals without line absorption complications.

Improvement of GCM Diagnostics

We have rewritten parts of the GCM diagnostics package to facilitate GCM intercomparisons such as those that have been conducted by Cess *et al.* This includes extracting the GCM output of cloud radiative forcing in Method II and Method III formats to enable more accurate intercomparisons between other GCM results and observational data from ERBE.

We have test-run a radiative-convective-advective equilibrium model to analyze the latitudinal dependence of GCM feedbacks (Lacis and Sato, 1993). We used zonally averaged annual mean climatologies of GCM output from several GCM experiments for globally uniform forcing for 1.02 S_0 and doubled CO_2 simulations. In both cases, atmospheric water vapor was found to be the principal positive feedback, and snow/ice albedo was a strong positive feedback at high latitudes. Cloud and advected energy transport feedbacks show significant latitudinal changes with substantial cancellation between these two feedbacks.

We have also made intercomparisons of GCM results with ERBE and ISCCP satellite data (Carlson and Wolf, 1993). These comparisons are diagnostic of both the radiative and cloud prediction parameterizations that are being tested 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. 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. This produces a strong positive feedback due to water vapor.

Publications Supported by ARM

The following publications were supported by funding provided by the U.S. Department of Energy through an Interagency Agreement under the Atmospheric Radiation Measurement Program.

Cess, R.D., and 32 co-authors, 1991: Interpretation of Snow-Climate Feedback as produced by 17 General Circulation Models. *Science*, **253**, 888-892.

Del Genio, A. D., A. A. Lacis and R. A. Ruedy, 1991: Simulations of the effect of a warmer climate on atmospheric humidity. *Nature*, **351**, 382-385.

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Lacis, A., J. Hansen, and M. Sato, 1992: Climate forcing by stratospheric aerosols. *Geophys. Res. Lett.*, **19**, 1607-1610.

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Randall, D.A., and 30 co-authors, 1992: Global, seasonal cloud and radiation variations from satellite radiance measurements. *J. Geophys. Res.*, **97**, 3711-3724.

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Cess, R.D., and 29 Co-authors, 1993: Intercomparison of CO_2 radiative forcing in atmospheric general circulation models. Submitted to *Nature*.

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Fu, R., W.T. Liu, A.D. Del Genio and W.B. Rossow, 1993: Reply to "A thermostat in the tropics?" by V. Ramanathan and W. Collins. *Nature*, **361**, 412.

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Pollack, J.B., D. Rind, A.A. Lacis, and J.E. Hansen, 1993: GCM Simulations of Volcanic Aerosol Forcing I. Climate Changes Induced by Steady State Perturbations. *J. Climate*, (in press).

Rind, D., and A. Lacis, 1993: The role of the stratosphere in climate change. *Surveys in Geophysics*, **14**, 133-165.

Tipping, R.H., and Q. Ma, 1993: Semi-empirical approach for the far wings of spectral lines: Application to the water continuum. In *Spectral Line Shapes*. Vol. **7** , (in press).

ARM Presentations

The following presentations were supported by funding provided by the U.S. Department of Energy through an Interagency Agreement under the Atmospheric Radiation Measurement Program. Presentations were made at the American Meteorological Society sponsored Fourth Symposium on Global Change Studies held January 17-22, 1993 at Anaheim, California.

Cairns, B., 1993. Inter- and intra-annual cloud variations from satellite based climatologies. *Fourth Symposium on Global Change Studies*, Jan 17-22, 1993, American Meteorological Society, pp. 245-248.

Carlson, B.E. and A.B. Wolf, 1993. Spatial and temporal characterization of diurnal cloud variability. *Fourth Symposium on Global Change Studies*, Jan 17-22, 1993, American Meteorological Society, pp. 98-103.

Del Genio, A.D, M.-S. Yao, and C.E. Wendell, 1993. GCM feedback sensitivity to interactive cloud water budget parameterization. *Fourth Symposium on Global Change Studies*, Jan 17-22, 1993, American Meteorological Society, pp. 176-181.

Lacis, A.A, and M. Sato, 1993. GCM feedback assessment with a 2-D Radiative-Convective-Dynamic equilibrium model. *Fourth Symposium on Global Change Studies*, Jan 17-22, 1993, American Meteorological Society, pp. 198-202.

Ma, Q., and R.H. Tipping, 1993. Theory and results for water vapor continuum absorption. *Fourth Symposium on Global Change Studies*, Jan 17-22, 1993, American Meteorological Society, pp. 214-219.