

Final Performance Report for DE-AI05-90ER61074, "Modeling of Clouds and Radiation for Developing Parameterizations for General Circulation Models", Drs. Owen B. Toon and Douglas L. Westphal, program directors.

SUMMARY

We have used a hierarchy of numerical models for cirrus and stratus clouds and for radiative transfer to improve the reliability of general circulation models. Our detailed cloud microphysical model includes all of the physical processes believed to control the lifecycles of liquid and ice clouds in the troposphere. We have worked on specific GCM parameterizations for the radiative properties of cirrus clouds, making use of a mesoscale model as the test-bed for the parameterizations. We have also modeled cirrus cloud properties with a detailed cloud physics model to better understand how the radiatively important properties of cirrus are controlled by their environment. We have used another cloud microphysics model to investigate of the interactions between aerosols and clouds. This work is some of the first to follow the details of interactions between aerosols and cloud droplets and has shown some unexpected relations between clouds and aerosols. We have also used line-by-line radiative transfer results verified with ARM data, to derive a new set of gas absorption data for the sort of rapid radiative transfer models used by GCMS. In total 9 people, two of whom are graduate students, have been working part or full time on this and other projects related to our work for DOE.

FINAL REPORT

We used a hierarchy of numerical models for cirrus and stratus clouds and for radiative transfer to improve the reliability of general circulation models. Our detailed cloud microphysical model includes all of the physical processes believed to control the lifecycles of liquid and ice clouds in the troposphere. Below we outline work on GCM parameterizations, cirrus cloud studies, investigations of the interactions between aerosols and clouds, as well as studies of radiative properties of clouds.

We have developed a consistent treatment of cirrus cloud microphysical and radiative processes for use in GCMs. The research-grade GCMs are faced with two related problems: (1) the bulk-water cloud parameterization assumes size distributions, particle shapes, and process rates that are inappropriate for cirrus; and (2) the radiation codes use size distributions and particle shapes that are decoupled from, and inconsistent with, those used in the microphysics. We have studied these problems using the PSU/NCAR MM4 mesoscale model which employs a bulk-water cloud scheme similar to those being incorporated in GCMs. As an example of the first problem, we found that the original cloud scheme developed by Lin *et al.* and Hobbs *et al.*, and widely used, assumed too many large cloud particles and underestimates the total number and total surface area. As a result, the bulk fall velocity, accretion, and other processes were overestimated. We have

applied reasonable size and shape assumptions to the microphysical processes in the bulk-water scheme and are comparing these with observations and with results from our detailed cloud model. We also found that the present ice nucleation scheme overestimated the production of ice. Using our detailed one-dimensional cloud model, we have developed a new parameterization of the production of ice crystals for use in bulk-water models and are presently testing the parameterization in three-dimensional simulations (Jensen, *et al.*, 1995, Westphal, 1995). When completed, these improvements can be easily applied to GCMs.

The second problem stems from the historical lack of explicit cloud prediction in GCMs. As a result, parameterizations of cloud optical properties have been simple, and at best, functions solely of ice water content. However, research-grade GCMs now use bulk-water models to predict clouds using various size and shape assumptions which, for internal consistency, should also be used in the optical calculations. We are developing new formulations for optical properties that use the same size and shape assumptions that are used in the microphysical model.

Another of our activities has been aimed at tropical clouds, anticipating the ARM tropical measurements. We have begun by modeling the subvisible cirrus near the tropical tropopause. These clouds were observed frequently during the recent CEPEX experiment over the western Pacific and are believed to play an important role in the radiative budget near the tropopause. The first objective of this work has been to understand the physical processes responsible for the formation and persistence of these clouds. In particular, we want to understand why the subvisible cirrus is ubiquitous over the tropical western Pacific, but essentially absent at midlatitudes and at other tropical longitudes. We have modeled the genesis of the clouds due to both outflow from convective anvils and in situ nucleation near the tropopause. In a manuscript submitted to Journal of Geophysical Research, we argue that in situ nucleation near the tropical tropopause is likely, and large ice crystal number densities should be generated due to the extremely low temperatures. These large ice number densities will limit crystal growth and allow the crystals to remain in narrow layers near the tropopause without precipitating out. We have shown that at the warmer midlatitude tropopause, fewer ice crystals should nucleate, resulting in more rapid cloud dissipation due to precipitation.

The second subvisible cirrus issue we have addressed is their possible impact on the stratospheric water budget. Stratospheric water vapor can be critical to the earth's heat budget, and the processes controlling the transport of water into the stratosphere are not currently understood. We have simulated ice cloud formation driven by motions on time scales ranging from gravity waves (1-2 hours) to continental-scale lifting (up to 24 hours). We show that in situ ice cloud formation due to gravity waves in the lower stratosphere will not likely dehydrate the region since the ice crystals do not grow large enough (5-10 μm) to precipitate out and remove the water. Cloud formation driven by slow lifting over a longer time period will allow more dehydration since fewer crystals should nucleate and the crystals will have longer to grow and precipitate out. We also show that ice clouds which form in air slowly lifting near the tropopause may substantially reduce the flux of water vapor into the stratosphere (manuscript in preparation).

A third area of research is the coupling between cloud properties and aerosols. Although we have investigated cirrus clouds, most of this work has concentrated on stratus where such interactions have been observed. Our one-dimensional stratus model reproduces measurements of stratiform clouds in the marine boundary layer, though the model predicts a nearly saturated region above cloud base that may be an artifact of horizontal averaging. (Ackerman *et al.*, 1994). We have found that aerosol concentrations in the cloud-topped marine boundary layer depend strongly on their formation rate, but the relationship is not bistable as suggested by other researchers (Ackerman *et al.*, 1995a). We have also found that clouds can deplete aerosol concentrations in the marine boundary layer until the clouds themselves dissipate and the boundary layer collapses. By simulating the injection of aerosols (representing ship exhaust) into a collapsed boundary layer, we have found that long-lived, optically thick cloud lines can develop (Ackerman *et al.*, 1995b). The persistence of such 'ship tracks' can be explained by our model result that aerosol lifetimes increase with aerosol concentration.

In the area of radiative transfer we have developed new K-distributions from the HITRAN 92 database for rapid computing of infrared gaseous absorption and have successfully made radiative transfer calculations up to 35 km altitude. We have compared our results against line by line calculations made at AER (Bergstrom, *et al.*, 1994) and are working on the comparison to the SPECTRE data. We are currently optimizing the choice of K-terms and the spectral bands. These studies make direct use of ARM CART site data to validate the line by line radiative transfer code which is then used to develop the fast radiative transfer capability.

One of the major difficulties in computing the radiative transfer through cirrus clouds is to account for the scattering by non-spherical particles. In order to better understand the single scattering properties of ice-crystals, new geometrical optics calculations for ice particles with shapes more complex than simple hexagons are being conducted (Kinne, 1995). We are updating our non-spherical corrections for ice crystals.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PUBLICATIONS

1993, Ackerman, A.S., O.B. Toon, and P.V. Hobbs, Dissipation of Marine Stratiform Clouds and Collapse of the Marine Boundary Layer Due to the Depletion of Cloud Condensation Nuclei by Clouds, *Science*, 262, 226-229.

1994, Ackerman, A.S., O.B. Toon, and P.V. Hobbs, Reassessing the dependence of cloud condensation nucleus concentration on formation rate, *Nature*, 367, 445-447.

1995a, Ackerman, A.S., O.B. Toon, and P.V. Hobbs, Numerical modeling of ship tracks produced by injections of cloud condensation nuclei into marine stratiform clouds, *J. Geophys. Res.*, in press.

1995b, Ackerman, A.S., O.B. Toon, and P.V. Hobbs, A model for particle microphysics, turbulent mixing, and radiative transfer in the stratocumulus-topped marine boundary layer and comparisons with measurements, *Journal of the Atmospheric Sciences*, in press.

1994, Bergstrom, R.W., S. Kinne and O.B. Toon Improved Prediction of Atmospheric Heating and Cooling Rates AMS conference on Atmospheric Radiation, Nashville, TN, January, 1994

1994a, Jensen, E.J., O.B. Toon, D.L. Westphal, S. Kinne, and A.J. Heymsfield, Microphysical modeling of cirrus 1: Comparison with 1986 FIRE IFO measurements, *J. Geophys. Res.*, 99, 10421-10442.

1994b, Jensen, E.J., O.B. Toon, D.L. Westphal, S. Kinne, and A.J. Heymsfield, Microphysical modeling of cirrus 2: Sensitivity studies, *J. Geophys. Res.*, 99, 10443-10454.

1994c, Jensen, E.J., and O.B. Toon, Ice nucleation in the upper troposphere: Sensitivity to aerosol number density, temperature, and cooling rate, *Geophys. Res. Lett.*, 21, 2019-2022.

1994d, Jensen, E.J., S. Kinne, and O.B. Toon, Tropical cirrus cloud radiative forcing: Sensitivity studies, *Geophys. Res. Lett.*, 21, 2023-2026.

1995, Jensen, E.J., D.L. Westphal, A.L. Walker, Parameterization of Ice Nucleation in the Upper Troposphere: Evaluation Using FIRE 1991 Simulations, submitted to *J. Atmos. Sci.*

1995, Kinne, S., T.P. Ackerman, M. Shiobara, A.J. Heymsfield, J. Wendell, L. Milosevitch and R.W. Bergstrom, Cirrus Cloud Radiative and Microphysical Properties From Ground Observations and in-situ Measurements during FIRE'91 and their Application to Illustrate Problems in Cirrus Solar Radiative Transfer Modeling, submitted to *J. Atmos. Sci.*

1995, Jensen, E.J., O.B. Toon, H.B. Selkirk and J. Spinhirne, On the formation and persistence of subvisible cirrus clouds near the tropical tropopause, submitted to *J. Geophys. Res.*

1995, Toon, O.B., Modeling the relationships between aerosol properties and the direct and indirect effects of aerosols on climate, in *Aerosol Forcing of Climate*, Academic Press, in Press.

1995, Westphal, D.L., Simulations of the dynamics, microphysics, and radiative transfer in a cirrus cloud system, submitted to *J. Atmos. Sci.*