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DEVELOPMENT AND TESTING OF AN AEROSOL / STRATUS CLOUD PARAMETERIZATION SCHEME FOR MIDDLE AND HIGH LATITUDES

Year 3 Technical Progress Report

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DISCLAIMER

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Abstract

At the present time, general circulation models (GCMs) poorly represent clouds, to the extent that they cannot be relied upon to simulate the climatic effects of increasing concentrations of greenhouse gases, or of anthropogenic perturbations to concentrations of cloud condensation nuclei (CCN) or ice nuclei (IN). The net radiative forcing of clouds varies strongly with latitude. Poleward of 30 degrees in both hemispheres, low-level clouds create a net cooling effect corresponding to radiative divergences of -50 to -100 W/m^2. It is likely that a combination of fogs, boundary-layer stratocumulus, and stratus clouds are the main contributors to this forcing. Models of the response of the microphysical and radiative properties of such clouds to changes in aerosol abundance, for a variety of large-scale meteorological forcings, are important additions to GCMs used for the study of the role of Arctic systems in global climate.

The overall objective of this research is the development of an aerosol / cloud microphysics parameterization of mixed-phase stratus and boundary-layer clouds which responds to variations in CCN and IN. The parameterization is to be designed for ultimate use in GCM simulations as a tool in understanding the role of CCN, IN, and Arctic clouds in radiation budgets. Several versions of the CSU RAMS (Regional Atmospheric Modeling System) will be used during the course of this work. The parameterizations developed in this research are intended for application in a single-column cloud model, designed as an adaptive grid model which can interface into a GCM vertical grid through distinct layers of the troposphere where the presence of layer clouds is expected.

Our choice of system to be parameterized is clearly applicable to the planned ARM CART site on the North Slope of Alaska, and thus we plan to use data from this site in developing and testing our models. In addition, modeling of Arctic synoptic, mesoscale and large-eddy-scale flows, which serve as the setting for the microphysical modeling, are extensions of the standard capabilities of RAMS that have been added in this model development activity.

I Overall Project Goals and Objectives

The overall objective of this research is the development of an aerosol / cloud microphysics parameterization of mixed-phase stratus and boundary-layer clouds which responds to variations in CCN and IN. The parameterization is to be designed for ultimate use in GCM simulations as a tool in understanding the role of CCN, IN, and Arctic clouds in radiation budgets. Several versions of the CSU RAMS (Regional Atmospheric Modeling System) will be used during the course of this work.

Our choice of system to be parameterized is clearly applicable to the planned ARM CART site on the North Slope of Alaska, and thus we plan to use data from this site in developing and testing our models. In addition, modeling of Arctic synoptic, mesoscale and large-eddy-scale flows, which serve as the dynamic environment for the microphysical modeling, are extensions of the current capabilities of RAMS and have required some model development activity. A major part of our effort in Year 3 has been testing the microphysical scheme and its interactions with drizzle formation and ice precipitation and with a new radiative transfer model. The case study we are working with has shown high sensitivity to the treatment of microphysics.

II Update of Year 2 Accomplishments and Report of Year 3 Progress to Date

The following subsections describe our progress in the second part of Year 2 (May - October 1996, not covered in the Year 2 Progress Report submitted May 1996), and during Year 3 to date.

1 Completion of Microphysical Scheme Development

One of the important findings in our earlier work was the inapplicability to the Arctic stratus environment of commonly-used drizzle bulk parameterizations, which use information on a single moment (*e.g.*, liquid water content) to predict the onset and magnitude of drizzle. These schemes failed to produce precipitation in case study simulations which clearly indicated the presence of drizzle. In contrast, simulations with our bin-resolving microphysics showed much better agreement with observations. This encouraging result is tempered by the computational costs of the bin-resolving model; two-dimensional simulations are feasible, but for more realistic three-dimensional studies, only a very limited number of cases, with reduced domain size and simulation time, can be performed.

To address this issue, we developed a new hybrid microphysical scheme which combines features of the bin-resolving microphysics with those of the bulk model. Specifically, the prognostic variables are the first and third moments of the drop distribution, which represent the total number of droplets and the total mass of liquid water. These variables are transported according to RAMS advection and diffusion schemes. During the microphysics time step, they are distributed into bins according to a preselected distribution function; our present implementation employs lognormal functions. Our moment-conserving techniques are then applied to the binned variables to predict the evolution of the drop size distribution and the onset of drizzle formation. After the call to the microphysics subroutines, the new number and mass concentrations are determined, and sent to the dynamics portion of the code for the next transport time step.

Initial results with the new hybrid scheme were quite encouraging. With appropriate selections of the lognormal basis functions, excellent agreement was found between the full bin microphysics and the hybrid scheme for both the onset of drizzle and the cloud microphysical properties passed to the radiation scheme, with a reduction of 30% in computational time. The development of this new scheme has been a major achievement in this work, since the computational savings realized make three-dimensional LES runs much more feasible; our work in Year 1 demonstrated the importance of 3D studies. The hybrid scheme is also applicable to the representation of CCN (aerosol) and enables us to add more complex chemistry than would be possible with the full bin microphysics.

During Year 2, we also made substantial progress on the implementation of ice-phase bin microphysics into the RAMS model. Initial tests were conducted by our collaborator Dr. Tamir Reisin, followed by his extended visit to CSU in early summer 1996, during which he tested and revised the full implementation. We also discussed the applicability of the hybrid microphysics approach to the ice-phase variables, and are examining the feasibility of developing a similar scheme for those species.

2 Arctic Stratus Case Studies

We have been working with the 28 June 1980 case study from the Arctic Stratus Experiment in the Beaufort Sea region (e.g., Curry 1986). This warm stratus case is characterized by a multi-layered cloud deck with a surface fog and a well-mixed upper level cloud, capped by a warmer and drier air mass. To test our cold cloud microphysics, our strategy has been to cool down this sounding to produce transition-season and cold-season simulations, due to the lack of appropriate observational data for other seasons. We then vary model input parameters and examine the response of the simulation to these changes.

A primary focus in the second half of Year 2 was the development of the warm cloud case study into a manuscript that was submitted for publication in *Atmos. Res.* and is currently nearing completion of the review process. In that work, we showed that the boundary layer dynamical structure could become weaker if CCN concentrations were enhanced. We have also completed transition-season simulations that were presented at the 1997 ARM Science Team Meeting. Those studies showed that the production of ice caused an initially vigorous cloud deck to quickly begin dissipating as the ice particles removed water from the cloud.

3 Radiation Scheme

Existing radiation parameterization schemes are not necessarily applicable to high latitudes. Simple two-stream models may exhibit large errors in the Arctic, because of the high zenith angles and moderate optical depths. Our summertime stratus case study used a newly-developed two-stream radiative transfer model which was specifically designed for high latitudes, and which also accepts droplet size spectrum information for use in computing cloud radiative properties. The results showed a very high sensitivity to the input microphysical parameters, again underscoring the need for an accurate and detailed representation in the cloud model. Further aspects of the formulation, particularly behavior at low sun angles, are being examined.

4 Addition of Chemistry

The primary task in Year 3 has been the addition of chemical species to the models. We have been guided in our choice of species by the numerous Arctic aerosol characterization experiments reported in the literature. Chemical composition will influence CCN activation, in the initial cloud and in repeated cloud cycles, as well as the radiative transfer rates. Representation of interactions among species will be one of the major challenges yet to be met; in our current work, we have assumed an initial sulfate aerosol composition that can vary in the extent of neutralization by ammonia. We have included S(IV) to S(VI) oxidation processes in the aqueous phase, and assume that this sulfate remains in the original CCN particle when the drop evaporates. In this way, cloud processing changes both the size of the original CCN, and the ammonium-to-sulfate ratio and hence the thermodyamic properties. We have modified the activation and solute effect terms in our cloud microphysics to account for arbitrary ammonium-to-sulfate ratios.

Due to the additional complexity introduced by variable particle chemical composition, we have developed a unique box-model framework for the testing of our schemes, and particularly, their effect on the aerosol population. The box model includes explicit microphysics and detailed chemistry, and are driven by trajectories diagnosed from our 2D and 3D cloud-resolving simulations. The usual box-model approach suffers from poor representations of dynamics and cloud interactions (e.g., an adiabatic parcel and LWC are usually assumed). Our trajectory-driven approach overcomes this objection and includes realistic in-cloud residence times during which the processing of gases and particles can take place. We can use this framework in two modes: (1) as a stand-alone model to test our new modules, and to determine which processes are significant enough to merit inclusion in the full dynamical model; and (2) as a means of simulating the overall cloud effects directly. To accomplish (2), we have been working on methods for appropriately averaging the results from a large number of trajectories, with the idea that the ensemble of trajectory runs is equivalent to performing a run with the full cloud-resolving model. This is an exciting concept for chemistry simulations, since more species and more detailed reaction mechanisms can be included in a box model than would be feasible in the cloud-resolving model.

III Summary of Work to be Completed

Our progress to date is on track with the tasks and milestones laid out in our original proposal. We will complete the development and testing of the parameterization scheme of mixed-phase stratus and boundary layer clouds, which is able to respond to varying vertical profiles of CCN and IN.

1 Completion of Chemistry Scheme Development and Testing

The scheme described in item (4) above will be tested further, particularly the feasibility of using the ensemble of trajectories to simulate the chemical processing occurring in Arctic stratus.

2 Applications to Single-Column Modeling

The ultimate goal of this work is to develop the components of a single-column model, designed as an adaptive grid model which can interface into a GCM vertical grid through distinct layers of the troposphere where the presence of layer clouds are expected. We intend to include aerosol chemistry and CCN and cloud drop physics, deduced from our LES / explicit microphysics and trajectory-driven box model simulations.

3 Manuscript Preparation and Submission

We intend to report the results of our completed studies in the scientific literature.

IV Publications To Date

Development and testing of an aerosol-stratus cloud parameterization scheme for middle and high latitudes. P.Q. Olsson, M.P. Meyers, S.M. Kreidenweis, and W.R. Cotton, presented at the DOE Fifth Annual Science Team Meeting, Atmospheric Radiation Measurement (ARM) Program, San Diego, CA, March 20-23, 1995.

Challenges to modeling Arctic stratus clouds. W.R. Cotton, S.M. Kreidenweis, P.Q. Olsson, J.Y. Harrington, M.J. Weissbluth, and G. Feingold, Proceedings of the Workshop on Cloud Measurements and Models, ETL, Boulder, CO, November 1995.

Cloud-resolving simulations of warm-season Arctic stratus clouds: Exploratory modeling of the cloudy boundary layer. P.Q. Olsson, W.R. Cotton and S.M. Kreidenweis, presented at the Arctic System Science Modeling Workshop, Boulder, CO, January 14-15, 1996.

Cloud-resolving simulations of warm-season Arctic stratus clouds. P.Q. Olsson, G. Feingold, Jerry Y. Harrington, W.R. Cotton, and S.M. Kreidenweis, presented at the DOE Sixth Annual Science Team Meeting, Atmospheric Radiation Measurement (ARM) Program, San Antonio, TX, March 4-7, 1996.

Exploratory cloud-resolving simulations of cold-season Arctic stratus clouds. W.R. Cotton, T.G. Reisin, S.M. Kreidenweis, G. Feingold, P.Q. Olsson, and J.Y. Harrington, presented at the 12th International Conference on Clouds and Precipitation, Zurich, Switzerland, August 19-23, 1996.

Cloud-resolving simulations of Arctic stratus. J.Y. Harrington, W.R. Cotton, S.M. Kreidenweis, G. Feingold, T. Reisin, and P.Q. Olsson, presented at the DOE Seventh Annual Science Team Meeting, Atmospheric Radiation Measurement (ARM) Program, San Antonio, TX, March 4-7, 1997.

Cloud-resolving simulations of Arctic stratus. J.Y. Harrington, G. Feingold, W.R. Cotton, and S.M. Kreidenweis, Proceedings of the Twelfth Symposium on Boundary Layers and Turbulence, Vancouver, B.C., Canada, July 18-August 1, 1997.

Exploratory cloud-resolving simulations of boundary layer Arctic stratus clouds. Part I: Warm season clouds. P.Q. Olsson, Jerry Y. Harrington, G. Feingold, W.R. Cotton, and S.M. Kreidenweis, submitted to *Atmos. Res.*, in review.