DOE/ER/61958-FINAL

DOE/ER/61958--T1

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

Final Technical Progress Report

For Period of Activity, Years 1 – 3:

November 1, 1994 - October 31, 1998
(including no-cost extension)

Sonia M. Kreidenweis, Principal Investigator
William R. Cotton, Co-Principal Investigator

Colorado State University
Dept. of Atmospheric Science
Ft. Collins, CO 80523

May 20, 1999

Prepared for

U.S. DEPARTMENT OF ENERGY
Atmospheric Radiation Measurement Program
GRANT #: DE-FG03-95ER61958

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

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

U.S. DEPARTMENT OF ENERGY
Atmospheric Radiation Measurement Program
GRANT #: DE-FG03-95ER61958

Sonia M. Kreidenweis, Principal Investigator
William R. Cotton, Co-Principal Investigator
Colorado State University
Dept. of Atmospheric Science
Ft. Collins, CO 80523

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 long-term objective of this research was 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 work plan was to perform simulations of these cloud systems to gain understanding of their dynamics and microphysics, especially how aerosols affect cloud development and properties, that could then be used to guide parameterizations. Several versions of the CSU RAMS (Regional Atmospheric Modeling System), modified to treat Arctic clouds, have been used during the course of this work. We also developed a new modeling system, the Trajectory Ensemble Model, to perform detailed chemical and microphysical simulations off-line from the host LES model. The increased understanding of the cloud systems investigated in this research can be applied to 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.

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. Our choice of system is clearly applicable to the ARM CART site on the North Slope of Alaska, and thus upcoming data from this site are expected to be useful in further testing of the models developed in this work.

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) were 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 data from this site were sought 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, were extensions of the existing capabilities of RAMS and required some model development activity. A major part of our involved testing the microphysical scheme and its interactions with drizzle formation and ice precipitation, and with a new radiative transfer model. A case study we investigated showed high sensitivity to the treatment of microphysics.

Aerosols and chemistry can be included in RAMS in only a rather crude way. Yet, cloud properties depend strongly on aerosol characteristics, and clouds in turn modify the particles that are processed through them. To investigate these interactions, we developed a hybrid approach, the Trajectory Ensemble Model, that uses dynamical fields from RAMS to drive parcels that include detailed descriptions of aerosol-cloud interactions. The goal was to understand how these interactions occur so that their effects can be included properly in simpler models.

II Accomplishments

1 Mesoscale Model Development

RAMS has traditionally been used mainly for mesoscale simulations at middle latitudes, particularly over the lower 48 states. To perform simulations in the high-latitude and Arctic regions, several modifications were necessary. First, the RAMS ISAN packages (data assimilation, objective analysis, and model initialization routines) were extended to operate in the polar region and across the International Date Line. Second, ice as a surface-cover type was available in RAMS, but was associated with land surfaces. Additionally, since flux differences between water and ice surfaces are so large, the subgrid parameterization for "mixed" regions are quite important, especially near shores. A true sea-ice representation was developed, which was initialized with the monthly gridded data sets of Walsh and Johnson (1979). Third, the eddy diffusivities used in most models, including RAMS, are not appropriate for the extremely stable atmosphere of the Arctic. Our initial simulation case study did not have the extreme conditions we expect for more "typical" Arctic weather systems, which allowed us to use existing RAMS options to explore the storm dynamics, including the vertical grid-spacing required to adequately resolve the stable wintertime boundary layer dynamics.

2 Synoptic-Scale Simulations

One of the most difficult aspects of simulating Arctic systems has been obtaining adequate data for model initialization. As an example of an Arctic mesoscale weather system, a synoptic-scale RAMS simulation of a heavily precipitating winter storm (February 28, 1989) was performed. The storm produced more than 10 times the typical observed total February precipitation at Point Barrow on Alaska's North Slope, and thus represents a rather unusual event. The simulation produced precipitation that appeared to be forced by both mesoscale baroclinic forcing and topography (in this case, an upslope component over the Brooks Range). Pristine ice and snow, aggregates, and graupel were predicted in different altitudes and regions of the domain. The results of this simulation were reported at the DOE/ARM Science Team Meeting, March 19 - 23, 1995.

This successful initial case study was used to test model sensitivity to important parameters. These include the effects of choice of vertical grid spacing in the boundary layer; the effect of model domain height on the evolution of synoptic-scale dynamics; and the effect of the choice of cloud microphysics schemes (one-moment vs. two-moment). Additionally, preliminary results suggested that an investigation of the contribution of orographic flow to snow deposition at Point Barrow might be of interest.

3 Cloud and Aerosol Microphysical Scheme Development

a. CCN activation parameterization. We devised a direct, non-iterative implicit algorithm for representing CCN activation and initial growth simultaneous with vapor and heat fluxes to larger ice and liquid hydrometeors which permits long computational time steps in RAMS. The method makes use of the ice-liquid potential temperature which is a prognostic variable and is conservative in both advective and vapor diffusional processes. The method also employs a pre-computed table of CCN activation numbers and droplet sizes based on integrations of a detailed cloud model run on a very small time step for the duration of the longer time step used in the dynamic model. This table is a function of five atmospheric parameters: temperature, two CCN activation parameters, dynamic supersaturation production rate, and fraction of CCN already activated. The two CCN activation parameters that are independent parameters of the table are C and k in the well-known CCN activation equation

$$N = CS^k.$$

This formula gives the number N of CCN activated as a function of supersaturation S and of C and k, which are empirical properties of the local CCN population and depend on the number, size distribution, and chemistry of the CCN. The formula has been found to adequately describe cloud droplet activation in a number of laboratory and field studies and has been widely used. We constructed the CCN activation tables by independently varying C, k, temperature, the number of CCN assumed to be already activated, and the dynamic production rate of S, and run a detailed model of vapor diffusional growth of newly activated CCN for each combination of the five parameters. Other parameters such as pressure were found to be of negligible importance in determining results of the detailed model and, hence, the table values.

In normal simulations in RAMS, values are accessed from the pre-computed tables to determine the number of newly activated CCN and the mass of water of newly activated cloud droplets each time step. Initial tests of this scheme show the method to be computationally stable and to give realistic results.

b. Drizzle parameterization. One of the important findings in our early 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 was 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.

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 was a major achievement in this work, since the computational savings realized made three-dimensional LES runs much more feasible; our work early on demonstrated the importance of 3D studies. The hybrid scheme was implemented into several versions of RAMS and its fully tested version has become one of the "standard" schemes used in Arctic simulations.

c. **Ice-phase microphysics.** The RAMS bin microphysics model was extended to include the ice-phase bin microphysics model developed by Reisin *et al.* (1996). It consists of three (ice crystals, aggregates and graupel) or five (pristine ice, rimed ice, aggregates, graupel and hail) ice species plus liquid cloud droplets and raindrops. The mass distribution functions of the different species are divided into 34 spectral bins spanning the range of masses found in clouds. The method of multi-moments (Tzivion *et al.*, 1987) is used in the numerical solution of the different stochastic equations that describe the microphysical processes:

- activation of drops (Stevens *et al.*, 1996)
- condensation / evaporation (Tzivion *et al.*, 1989 ; Stevens *et al.*, 1996)
- collision-coalescence of drops (Tzivion *et al.*, 1987)
- binary breakup of drops (Low and List kernels) (Feingold *et al.*, 1988)
- nucleation of ice crystals (deposition, condensation-freezing, contact and homogeneous) (Walko *et al.*, 1995)
- secondary ice production (Hallett-Mossop mechanism) (Mossop, 1985; Ferrier, 1994)
- sublimation / deposition (Reisin *et al.*, 1996)
- ice-ice and drop-ice interactions (riming, accretion, ...) (Reisin *et al.*, 1996)
- melting and shedding (Reisin *et al.*, 1996)
- sedimentation of drops and ice particles

The applicability of the hybrid microphysics approach to the ice-phase variables was investigated by comparing results from the detailed and the hybrid methods.

4 New Two-Stream Radiation Code

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, described below, used a newly-developed two-stream radiative transfer model which was specifically designed for high latitudes, and which responds to the detailed cloud droplet and ice particle spectra, including the ice particle habits. The case study showed a very high sensitivity to the input microphysical parameters, again underscoring the need for an accurate and detailed representation in the cloud model.

Equations for both solar and infrared radiation are solved for three model gases and atmospheric particulates. The gases considered in the model include H_2O_v, O_3, and a gas modified as suggested by Ritter and Geleyn (1992), which considers CO_2 with average climatological CH_4, O_2 and NO_2 mixing ratios included in the computations. Gaseous absorption in the model is computed by the fast exponential sum-fitting of transmissions as discussed by Ritter and Geleyn (1992) and Edwards (1996). This method is utilized for the band structure of Ritter and Geleyn (1992) for the fluxes in the solar and the net fluxes in the infrared. Rayleigh scatter and continuum absorption are treated as if they are independent of wavelength (gray) across a given band. Rayleigh scatter and continuum absorption are computed with the formulae given by Slingo and Schrecker (1982) and Liou (1992), respectively.

The optical properties of water drops are treated with the methodology of Slingo and Schrecker (1982). Band-averaged values of the single scatter albedo (ω_p) and the extinction coefficient β_{ext}) are computed and fit as functions of the characteristic diameter (D_n) of a generalized gamma distribution function (Walko *et al.*, 1995). Absorption and extinction cross-sections are computed using anomalous diffraction theory (ADT) modified for spheres as discussed in Mitchell (1997). Parametrizations of ω_p and β_{ext} for ice crystals follows Mitchell and Arnott (1994) in which hydrometeor absorption is reduced through an effective path-length parametrization. Extinction properties are computed assuming equivalent volume spheres; ADT then follows the methods of Mitchell (1997). Asymmetry parameters are computed assuming spherical ice particles.

The optical property computations for the bin model representations follow a somewhat different approach. Since the bin representation does not have a distribution shape restriction, assuming a gamma or log-normal distribution introduces unnecessary errors in the computations of the scattering and absorbing properties. To alleviate this problem we developed a method to compute the optical properties for each bin and then sum the area-weighted properties to find the total β_{ext}, ω_p and g for the distribution function. Errors for this method are largest (up to 6%) when there is a preponderance of small particles ($D < 5$ μm). For the warm microphysics (drops only), Lorenz-Mie theory is used in the computations of the optical properties. For the ice microphysics, Lorenz-Mie solutions for ice spheres or for oblate and prolate spheroids (Asano and Sato, 1980) are utilized.

5 Arctic Stratus Case Studies

a. Summertime stratus. The new hybrid warm-cloud microphysical scheme was tested against the bin-resolving microphysics in a case study from the Arctic Stratus Experiment in the Beaufort Sea region (e.g., Curry 1986). The 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. The case was spun up for four hours using the LES version of RAMS with a bulk microphysics scheme. Although most features of the case were reproduced, the shear layers in the initial sounding in the lower domain tended to mix the fog layer and reduce LWC. This observation, along with general concerns about representing dynamics of the Arctic boundary layer, led us to investigate other turbulence closure schemes that may be better suited to the stable and neutral regimes typically found in the Arctic. As a result, we implemented a version of the Deardorff scheme.

The results from the four-hour spin-up were then used to initialize two-hour sensitivity runs with both the hybrid and the bin-resolving microphysics, varying initial CCN number concentrations. That work showed that the boundary layer dynamical structure could become weaker if CCN concentrations were enhanced. The case with low CCN (100 cm^{-3}) was classified as weakly drizzling, whereas cases with CCN concentrations of 300 and 500 cm^{-3} were similar and nonprecipitating. Those cases with higher CCN also had more radiative cooling near cloud top. The precipitating case produced sub-cloud cooling, which was partially responsible for more vigorous eddies in that simulation. The hybrid scheme performed well, as compared with the full bin microphysics, particularly when the choice of fixed drop distribution breadth parameter was adjusted to be more in line with that computed in the bin model. This case study was described in a paper that has appeared in *Atmospheric Research.*

b. Mixed-phase stratus. When this project was initiated, no good case studies of mixed-phase and cold arctic clouds existed. We dealt with the lack of appropriate observational data for other seasons by cooling down the summertime sounding to produce transition-season and cold-season simulations to test our cold cloud microphysics. We then varied model input parameters and examined the response of the simulation to these changes.

At the ICCP conference in Switzerland, Cotton *et al.* (1996) described preliminary results of simulations with the mixed-phase bin microphysics model coupled to the 2D RAMS cloud-resolving model. For that study, we interfaced the new radiation code described above by approximating the particle size-spectra predicted with the bin model with gamma-size spectra. The simulations were performed by cooling the sounding given in the warm microphysics case above by 7 °C while keeping the relative humidities constant. The results showed that, as the ice phase depleted the cloud liquid water in the model, the optical thicknesses diminished to the point that little cloud top radiative cooling occurred. This resulted in an almost complete collapse of the boundary layer with turbulence levels becoming so small that only thin stratus remained or the cloud completely dissipated. These results are reminiscent of those obtained by Ackerman *et al.* (1993; 1994) for a cloudy marine boundary layer, in which they reduced the production of CCN to the point that drizzle depletion of CCN dominated, cloud drop number concentrations and moisture decreased, cloud top radiative cooling was diminished, and the boundary layer collapsed.

These exciting results suggest that an important transition may take place in the dynamics of Arctic stratus clouds as the Arctic boundary layer is cooled to the point that the ice phase becomes the dominant precipitation process. That is, rapid particle removal by precipitation of ice depletes the boundary layer of particles and moisture, and an entirely different dynamical structure develops. We repeated those earlier simulations, but with some refinements in the radiation model, as we reported at the 1997 ARM Science Team Meeting. The refined model explicitly interacts with the particle-spectra predicted by the bin model, rather than approximating the size-spectra with a gamma distribution function. The results with the revised model showed similar characteristics to the earlier simulations. Cloud-top radiative cooling rates were enhanced with the bin optical property representation, which was due to a more appropriate response of the radiation to a narrowing water drop distribution function. This narrowing of the drop distribution function occurred via the loss of large particles due to freezing and collection mechanisms. The earlier, parametrized gamma function response does not allow for a narrowing spectrum and, thus, produces cooling rates at cloud top that are much less than that produced by the bin representation. However, even though the bin representation produces larger cloud top cooling rates, this effect is not enough to offset the reduction in buoyancy production caused by the loss of ice water mass from the cloud layer by sedimentation.

6 Trajectory Ensemble Model

Numerous arctic aerosol characterization experiments have been reported in the literature and served as guides to choises for particle number concentrations and chemical and physical properties. 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 is a major challenge; we assumed an initial sulfate aerosol composition that can vary in the extent of neutralization by ammonia. We 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 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 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 is driven by and ensemble of 500 trajectories diagnosed from our 2D and 3D cloud-resolving simulations (giving rise to the name "trajectory ensemble model"). 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 used this framework in two modes: (1) as a stand-alone model to test 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 developed 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. Our methodology and its application to several sensitivity studies are described in papers appearing in *J. Geophys. Res.*

The trajectory ensemble approach has also proved powerful in studying microphysical phenomena using more detailed model representations than can be included in the full RAMS. The approach was used to study the influence of radiation on growth of a population of drops in summertime arctic stratus. This work, reported in a paper submitted to *J. Atmos. Sci.*, showed that the inclusion of this effect triggered the onset of drizzle formation earlier, but did not lead to a strong change in the overall structure or evolution of cloud; these were more sensitive to the aerosol input, pointing again to the need for more work on the aerosol–cloud interactions that can occur in these systems.

7 A Single-Column Model for Layer Clouds

A single-column model was developed for simulating the stratocumulus-topped marine boundary layer (Golaz, 1998). It includes two different low-order turbulent closure schemes both based on the turbulent kinetic energy but with different formulations for the dissipation. The model has been coupled with a microphysical parameterization in order to be able to simulate precipitating stratocumulus clouds.

The model was first validated with an idealized non-precipitating stratocumulus case. Results from the single-column model compared favorably with results from a wide range of other models. In order to examine the ability of this model to capture the effect of drizzle on the boundary layer, simulations were done based on ASTEX data which had already been used in sophisticated large eddy simulations. The single-column model was able to produce realistic precipitation rates. Drizzle was found to have a significant impact on the boundary layer by producing a two-layer structure. The subcloud layer was stabilized by almost 1 K with respect to the cloud layer. Evaporation of drizzle in the subcloud layer decreased buoyancy production leading to a region of strongly reduced turbulent kinetic energy below the cloud layer. This reduction did not cause a decoupling of the boundary layer. Overall, effects of drizzle as seen by the single-column model appeared to be in reasonably good agreement with results from previous works. However, large eddy simulations have also shown that, although the boundary layer does not decouple, the nature of the coupling changes by becoming more cumulus-like. This change in the nature of the coupling was not captured by the single-column model.

III Publications Acknowledging Support From This Grant

a. Conference Presentations, Proceedings, and Technical Reports:

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.

The microphysical characteristics of convection in marine stratocumulus. Bjorn Stevens, William R. Cotton, and Graham Feingold, Preprints, Conference on Cloud Physics, Dallas, Texas, 15-20 January, 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 warm-season arctic stratus clouds. Olsson, P.Q., G. Feingold, J.Y. Harrington, W.R. Cotton, and S. Kreidenweis, Preprints, 12th International Conf. on Clouds and Precipitation, Zurich, Switzerland, 19-23 August 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.

Cloud processing of aerosol and gases in a trajectory ensemble model. S. Kreidenweis, G. Feingold, and Y. Zhang, Preprints, 1998 AMS Conference on Cloud Physics, Everett WA, August 1998.

Radiative impacts on the growth of drops in Arctic stratus. J.Y. Harrington, G. Feingold, and W.R. Cotton, Preprints, 1998 AMS Conference on Cloud Physics, Everett WA, August 1998.

The impact of radiative and microphysical processes on mixed-phase Arctic stratus. W.R. Cotton, J.Y. Harrington, and T. Reisin , Preprints, 1998 AMS Conference on Cloud Physics, Everett WA, August 1998.

b. Refereed Journal Articles:

Alexander, G. David, and William R. Cotton, 1998: The use of cloud-resolving simulations of mesoscale convective systems to build a convective parameterization scheme. *J. Atmos. Sci.*, 55, 2137-2161.

Olsson, P.Q., J.Y. Harrington, G. Feingold, W.R. Cotton, S.M. Kreidenweis, 1998: Exploratory cloud-resolving simulations of boundary-layer Arctic stratus clouds. Part I: Warm-season clouds. *Atmos. Res.*, 47-48, 573-597.

Harrington, J.Y., T. Reisin, W.R. Cotton, S.M. Kreidenweis, 1999: Cloud resolving simulations of Arctic stratus. Part II: Transition-season clouds. *Atmos. Res.*, 51, 45-75.

Harrington, J.Y., G. Feingold, W.R. Cotton, S.M. Kreidenweis, 1998: Radiative impacts on the growth of a population of drops within simulated summertime Arctic stratus. Submitted to *J. Atmos. Sci.*

Feingold, G., S. Kreidenweis and Y. Zhang, Stratocumulus processing of gases and cloud condensation nuclei. Part I: Trajectory ensemble model. *J. Geophys. Res.*, 103, 19,527-19,542,1998.

Zhang, Y., S. Kreidenweis and G. Feingold, Stratocumulus processing of gases and cloud condensation nuclei. Part II: Chemistry sensitivity analysis. *J. Geophys. Res.*, accepted.

c. Dissertations:

Harrington, Jerry Y., 1997: The effects of radiative and microphysical processes on simulated warm and transition season Arctic stratus. Ph.D. dissertation, Atmospheric Science Paper No. 637, Colorado State University, Dept. of Atmospheric Science, Fort Collins, CO 80523, 289 pp.

Zhang, Yiping, 1998: The effects of clouds on aerosol and chemical species processing, production and distribution in the boundary layer and upper troposphere. Ph.D. dissertation, Atmospheric Science paper No. 661, Colorado State University, Dept. of Atmospheric Science, Fort Collins, CO 80523, 155 pp.