Development and Testing of an Aerosol-Stratus Cloud Parameterization Scheme for Middle and High Latitudes

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Introduction

The aim of this new project is to develop an aerosol/cloud microphysics parameterization of mixed-phase stratus and boundary layer clouds. Our approach is to create, test, and implement a bulk-microphysics/aerosol model using data from Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) sites and large-eddy simulation (LES) explicit bin-resolving aerosol/microphysics models. The primary objectives of this work are twofold. First, we need the prediction of number concentrations of activated aerosol which are transferred to the droplet spectrum, so that the aerosol population directly affects the cloud formation and microphysics. Second, we plan to couple the aerosol model to the gas and aqueous-chemistry module that will drive the aerosol formation and growth.

We begin by exploring the feasibility of performing cloud-resolving simulations of Arctic stratus clouds over the North Slope CART site. These simulations using Colorado State University's regional atmospheric modeling system (RAMS) will be useful in designing the structure of the cloud-resolving model and in interpreting data acquired at the North Slope site.

The RAMS Model

RAMS is a completely new code that was derived from the merger of two modeling programs: the cloud modeling program under the direction of William R. Cotton and the mesoscale modeling program directed by Roger A. Pielke (Pielke et al. 1992). RAMS can be run either hydrostatically or non-hydrostatically and contains an interactive grid-nesting capability allowing a large number of telescoping grids or a number of simultaneous non-telescoping grids. Furthermore, RAMS is designed to be initialized from the objective analysis of standard atmospheric soundings and be driven by time-varying boundary conditions provided by standard 12-hourly soundings or from larger scale model grid point data such as the National Meteorological Center Nested Grid Model. This mechanism of data assimilation could be readily modified to allow interfacing with general circulation model grid-point data. Particularly useful features of RAMS for examining aerosol chemistry and aerosol impacts on clouds on the regional-scale are its ability to explicitly represent clouds of all sorts ranging from cumulus clouds to stratus and cirrus clouds including their interactions with atmospheric radiative transfer. Additionally, RAMS has the ability to represent surface properties including soil/ vegetation effects on the surface energy budget, sea ice, and snow-covered land surfaces.

Cloud Microphysics

A new microphysical scheme has been developed which allows two-moment prediction of the distribution function for each hydrometeor category, making the determination of each hydrometeor size spectra less arbitrary (Meyers 1995). This scheme predicts the mixing ratio and number concentration of rain, pristine ice crystals, snow, aggregates, graupel, and hail categories. The cloud microphysical scheme includes the use of a generalized gamma size-spectrum, for all hydrometeor categories (Walko et al. 1995). Some other relevant features of the new two-moment scheme include

- approximate solutions to the stochastic collection equation rather than the continuous-accretion model approach
- predictive equations for ice nuclei (IN)
- new heterogeneous and homogeneous ice nucleation parameterizations with analytical flux equations to predict mixing ratio and number concentration conversion from pristine ice crystals to snow due to deposition (no riming)

- diagnosed crystal habit dependent on temperature and saturation.

Model Development

RAMS has traditionally been used mainly for mesoscale simulations at middle latitudes, particularly over the lower 48 states. In order to perform simulations in the high latitude and arctic regions, several modifications of the standard RAMS version 3b are necessary. For example, the RAMS Isentropic Analysis package (data assimilation, objective analysis, and model initialization routines) has been extended to operate correctly in the polar region and across the International Date Line. The predictive model as well requires additional features to achieve the desired results.

Surface Parameterizations

An adequate representation sea ice is a very important requirement in any atmospheric model simulation of the marine arctic environment. Sea ice affects the longwave radiation in the winter months, while in the summer months the shortwave radiation budget is affected as well. Of more significance, the surface heat and moisture flux properties of sea ice and open water differ dramatically and can have a profound effect on the short- and long-term climate (Chapman and Walsh 1993). Furthermore, the southward extent of sea ice varies as much as 15°C seasonally (Walsh et al. 1993).

Monthly gridded data sets of northern hemisphere sea-ice percentage (Walsh and Johnson 1979) have recently become available through the National Center for Atmospheric Research and efforts are under way to incorporate this data into RAMS. The rather coarse nature of this data set (grid boxes of 111 km), and low temporal resolution (essentially “snapshots” for the last day of each month), may prove inadequate for verifiable simulations at the LES scale. Unfortunately, more resolved regional sea-ice data sets are not readily available.

Ice as a surface-cover type is already available in RAMS, and a snow-surface parameterization is currently in the development and testing stages.

New Microphysical Features

A major objective of this research project is to predict the effects of changes in the aerosol spectrum upon evolving cloud properties, for both cloud condensation nuclei and IN. Therefore, schemes for representing the activation of aerosol are an important focus. Since activation is sensitive to the predicted value of supersaturation, we use prognostic equations for the concentrations and mixing ratios of cloud water, rainwater, and all ice hydrometeor categories.

Currently RAMS is being updated to include prognostic equations for two aerosol species: one a dry aerosol species represented by a single mode, and the other a hygroscopic aerosol species represented by up to three modes. These four modes will allow for representation of aerosol size and chemistry under both “clear” and arctic haze conditions.

Assuming that the aerosol is distributed in a log-normal or gamma distribution, the number concentrations and mixing ratios of these species are explicitly predicted. Advection, turbulent diffusion, and removal by nucleation are considered. Moreover, cloud droplets are assumed to follow a gamma distribution, with concentration and mixing ratio of cloud droplets being predicted as well.

Tests are currently under way to ensure that predicted vapor concentrations, along with predictions for numbers of aerosol activated and numbers of drops and crystals, are reasonable. Furthermore the scheme is designed to be used with the relatively long time steps typically used in mesoscale models. As discussed below, an explicit bin-resolving microphysical model will also be used in RAMS LES experiments to help determine the appropriateness of the treatment in the two-moment model.

In addition to accurately representing the supersaturation, and relating this to the numbers of aerosol particles activated, the moment treatment should reflect the removal of larger-sized particles by activation, so that new aerosol mass is not activated in subsequent time steps. For simpler schemes where breadth parameters are fixed, updated number and mass concentrations are reallocated into larger-sized particles, creating “tails” from which mass is continuously activated. We are exploring a number of schemes designed to mitigate this problem.

We are also developing methods to “track” the aerosol mass through the cloud spectra so that evaporating drops or crystals will release particles that become re-suspended (Richardson 1995), as some of these particles may be altered by physical and chemical processes within the cloud.

Synoptic-Scale Simulations

The synoptic-scale flow is an important factor in the formation of arctic clouds, both in the transport of heat and moisture and in the long-range transport of trace gases and aerosols (Iversen 1989). High latitude synoptic-scale disturbances such as extra-tropical cyclones and baroclinic waves produce broad regions of vertical motion enhancing the production of hydrometeors and perturbing the ambient aerosol spectrum. Therefore it is important that the mesoscale model accurately simulate the larger-scale dynamics and the transfer of energy and enstrophy between scales.

To validate the model physics in the arctic environment, we are performing relatively coarse-grid simulations (100- and 50-km Δx) of a major winter storm which occurred over the arctic slope of Alaska on February 28, 1989 (see discussion below). Some of the important issues to be addressed by this and other sensitivity studies are

- the vertical grid-spacing required to adequately resolve the extremely stable wintertime arctic boundary layer dynamics
- relative merits of data assimilation and objective analysis on isentropic surfaces versus σ_z (terrain-following) surfaces
- the impact of long-range aerosol transport on arctic haze production and its consequent feedback on the radiation budget
- the effect of model domain height on the evolution of synoptic-scale dynamics.

Large Eddy Resolving Simulations

Parallel to the model development and testing at the large scale, LES experiments are planned to test the microphysical schemes.

To refine and test the two-moment, multiple-mode microphysics scheme, LES experiments will be run with explicit bin-resolving microphysics, applied to the aerosols (Richardson 1995) and cloud droplets (Feingold et al. 1994). The aerosol scheme uses assumed particle chemical composition for the activation process as well as for determining haze size under various relative humidities. The explicit-microphysics LES runs employ small time steps with accurate representation of fluctuations in supersaturation to capture the details of the aerosol/cloud interactions. We will also extend the bin model to include ice-phase hydrometeors (Reisin 1995).

A perhaps more rigorous test of the cloud model will be performed by implementing a "floating LES" within a mesoscale flow field. With current computer resources, it is not feasible to perform simulations with nested grids ranging from the synoptic-scale (~100 km Δx) down to the LES scale (~ 50-m Δx). To circumvent this restriction, we intend to perform LES simulations with time-varying boundary conditions, such boundary conditions being determined by the output of a multiple nested-grid mesoscale simulation. In this manner we may evaluate the time-dependent effects of long-range transport of aerosols in a horizontally inhomogeneous LES domain "advecting" in the mean mesoscale flow.

North Slope Case Study (February 28, 1989)

As an example of a mesoscale weather system simulation in the arctic, we here briefly describe a single grid RAMS simulation of a heavily precipitating winter storm occurring on February 28, 1989. This storm produced over 2 cm of precipitation (liquid-equivalent) at Point Barrow on Alaska's North Slope, more than 10 times the typical observed total February precipitation for this location. This rather unusual event occurred under a strong lower-and mid-tropospheric ridge of high pressure.

At the model initialization time of 0000 UTC February 28, a tongue of strong southerly surface winds extended from 50°N northward over the Bering Sea and through the Bering Strait. This low-level jet was advecting high θ_e air northward over a quasi-stationary polar front oriented zonally at about 75°N over the Arctic Ocean (Figure 1a). The resultant over-running produced a region of moderate to heavy snowfall south of the front, extending to the northern coastal areas of Alaska. Additionally, the moist flow over the Brooks Range in northern continental Alaska had a significant upslope component in the lowest 5 km of the atmosphere.

In less than 1 hour of simulation time, precipitation was occurring over the northern coast and Arctic Ocean. Figure 1b shows the cloud at 3000 m above sea level at 0800 UTC, after 8 hours of simulation time. Figure 2 shows vertical cross-sections of several ice mixing ratio fields at this time. The precipitation appears to be forced by both topographical and mesoscale baroclinic mechanisms. The pristine ice and snow mixing ratio maxima are both located north of the Brooks Range with peak values (0.01 and 0.02 g kg^{-1}, respectively) confined primarily above 3 km.

Aggregation is quite active in this region as shown by the aggregate mixing ratio field (Figure 2d). The aggregate field extends to lower altitudes with peak values (0.11 g kg^{-1}) much greater than the pristine ice and snow categories. Graupel is also simulated (not shown) in this region, indicating the presence of some supercooled cloud water north of the Brooks Range.

The results from this sensitivity simulation are encouraging in that they demonstrate the ability of the standard RAMS single-moment microphysics to perform credibly in the Arctic.

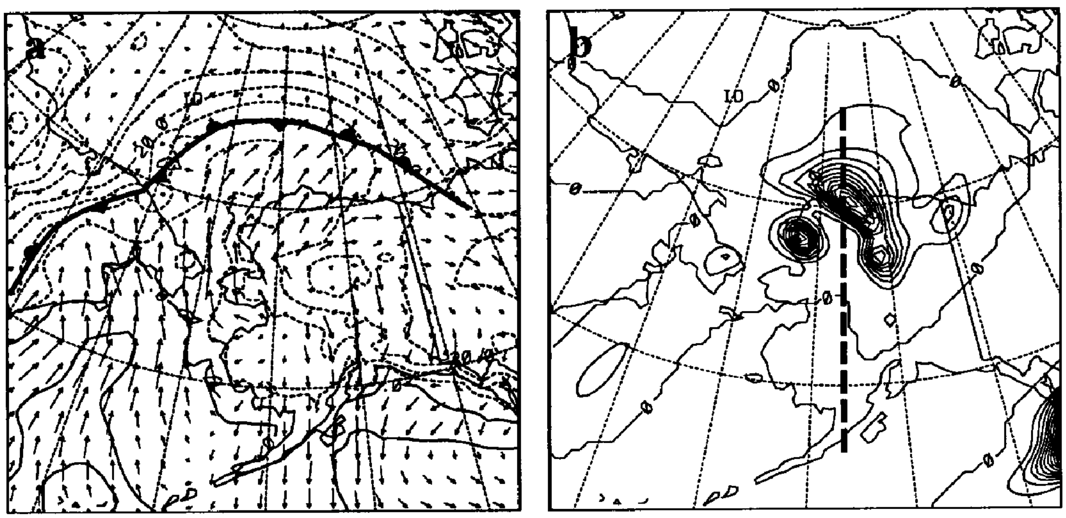

Figure 1. a) The surface winds, temperature (5°C contours) and frontal position for Feb. 28, 1989, at 0000 UTC, the initial time of the simulation. The strong southerly surface jet over the Bering Sea and Bering Strait with winds exceeding 25 m s^{-1} is providing significant positive low-level θ_e advection and upslope conditions for the Brooks Range in N. Alaska. b) Total ice mixing ratio at 0800 UTC and 3000 m above sea level, after 8 hours of simulation. The contour interval is 0.01 g kg^{-1} and the maximum value is 0.3 g kg^{-1}. The heavy dashed line shows the location of the N-S vertical cross sections shown in Figure 2.

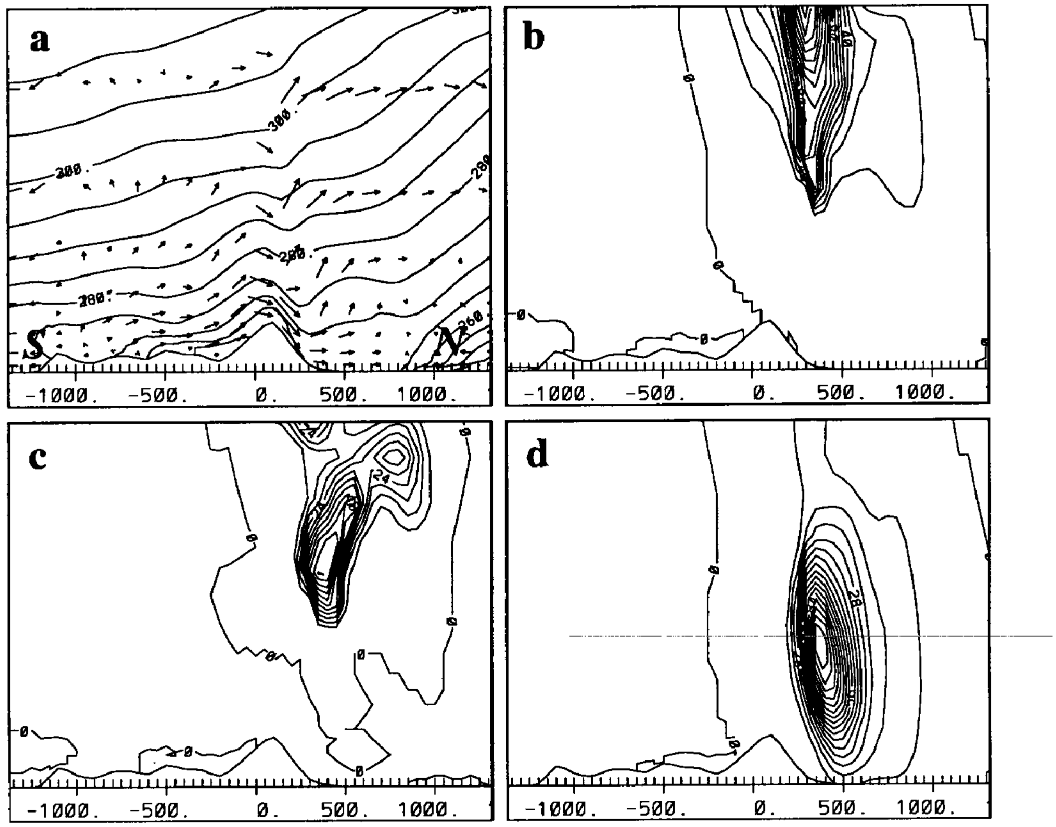

Figure 2. All cross-sections at time 0800 UTC, located along dashed line in Figure lb. Figures are oriented with south to the left as denoted in a. Only the lowest 6 km of the domain is shown in the figures. a) Wind vectors and potential temperature contours (5°C increments), maximum winds are 32 m s^{-1}; b) snow mixing ratio with a contour increment of 10^{-3} g kg^{-1} and a maximum value of 0.02 g kg^{-1}; c) pristine ice mixing ratio, contour interval of 6×10^{-4} g kg^{-1}; d) aggregate mixing ratio, contour interval of 7×10^{-3} kg^{-1} and a maximum of 0.11 g kg^{-1}.

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