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Title: **Mesoscale Numerical Prediction of Clouds and Cloud Effects**

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1. Introduction

Since 1991 a prototype forecasting version of the Regional Atmospheric Modeling System (RAMS) has been running in realtime on high-performance workstations to predict winds, temperatures, precipitation, agriculture and aviation impact variables (Thompson, 1993; Cotton et al., 1994; Beitler, 1994; Cotton et al., 1995). Beginning in 1995 the forecast model has been run with explicit bulk microphysics described by Walko et al. (1995). This version of the microphysics contained prediction of one moment of the hydrometeor categories, except for ice crystals where two moments was predicted. Gaudet (1996) showed that the use of the explicit bulk microphysics resulted in greatly improved forecasts of precipitation in the form of snowfall for high-elevation sites in Colorado. Forecasts at lower elevation sites, however, such as mountain valleys were of poorer quality because the 16 km grid spacing and the use of silhouette-averaging resulted in poor representations of the terrain in those regions. Nonetheless, this work has shown that mesoscale forecasts with explicit bulk microphysics is possible even on relatively modest computer workstations.

Beginning in 1996, a parallel-processing version of RAMS has been running on a cluster of IBM RISC workstations, and on an IBM SP-2, and more recently on a 8 processor HP/Convex Exemplar. Prototype forecasts with bulk microphysics with these models show that it is now possible to make mesoscale forecasts with grid spacing as small as 1 to 5 km with relatively modest investments in computer hardware over limited domains of a few hundred kilometers. Such high-resolution forecasts with explicit bulk microphysics permit applications of the models to prediction of precipitation and precipitation type (e.g., hail vs. low density graupel vs. rain, and freezing rain vs. snow), lightning, ceiling and visibility (including cloud cover, fog), aviation-impact variables including aircraft icing, turbulence, downbursts, and severe weather, and surface temperatures.

In this paper we use RAMS microphysics and new developments expected in the next few years to illustrate the state-of-the-art and the potential impacts on microphysics measurements in support of realtime forecast models.

2. Overview of Current 2-Moment Microphysics and Coupled Radiation Model

The RAMS bulk microphysics parameterization prognoses both mixing ratio and number concentration for rain, pristine ice, snow, aggregates, graupel, and hail, and predicts mixing ratio for cloud water. It is a further evolution of the microphysics model from the two-moment shcme described by Meyers et al. (1996). Number concentration prediction for cloud droplets still requires an accurate cloud nucleation scheme, which is currently under development and described below. Physical processes represented in the model include vapor and heat diffusion, collision and coalescence between all possible pairs of hydrometeor types including self-collection, melting and freezing, heterogeneous nucleation of ice through contact and deposition freezing, homogeneous nucleation of cloud droplets and haze into ice crystals, shedding of liquid water by hail, and sedimentation. Ice crystals are allowed to take on 5 different habits that are diagnosed based on cloud top temperature and humidity.

2.1 Computing heat, vapor diffusion and supersaturation

The latest two-moment version of the model employs a direct, non-iterative implicit algorithm for representing vapor and heat diffusion between the air and all hydrometeor species simultaneously. The vapor and heat diffusion equations are formulated implicitly based on future hydrometeor and air temperature and future vapor mixing ratio. The method makes use of the ice-liquid potential temperature that is a prognostic variable and is conservative in both advective and vapor diffusional processes. Inputs to the set of equations are current air and hydrometeor temperatures, vapor mixing ratio, and hydrometeor mixing ratio and number concentration, which are updated following the evaluation of advection, turbulent diffusion, sedimentation, and hydrometeor collisions. The implicit solution to the system of diffusion equations provides a stable and accurate solution to hydrometeor and vapor temperatures and mixing ratios. From these, an accurate supersaturation may be derived as long as activation of CCN is not occurring simultaneously.

2.2 Prediction of CCN activation and initial cloud droplet growth

A method has been developed for evaluating 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 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 activation scheme serves as the correction to supersaturation. The two CCN activation parameters that are independent parameters of the table are C and k in the well-known CCN activation equation of Twomey and Wojciechowski (1969).

$$N = C\,S^k,$$

where C and k are empirical properties of the local CCN population and depend on the number, size distribution, and chemistry of the CCN. We construct the CCN activation tables by independently varying C, k, the number of CCN assumed to be already activated, the dynamic production rate of S, and a function of pressure and temperature, and run a detailed model of vapor diffusional growth of newly activated CCN for each combination of the five parameters. Other parameters 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 fair results. However, evaluation of air parcel history in terms of an Eulerian grid cell rather than as a Lagrangian parcel have proven to cause unacceptable errors in predicted cloud droplet number in some cases. Thus, this method for evaluating CCN activation is being reformulated into a Lagrangian form prior to implementation in RAMS.

2.3 Current implementation of Level 3.5 in 2-moment bulk microphysics

Improvements have been made to the RAMS bulk microphysics code that employ results of a full bin model to more accurately represent the dependence of physical processes on hydrometeor size. The parts of the code in which this approach has been implemented are autoconversion of cloud droplets to rain, collection of cloud droplets by raindrops, and sedimentation. The new scheme, as described by Feingold et al. (1997), is designed to capture the essence of a bin microphysical scheme but with significantly lower computational expense. The scheme used a double basis function (lognormal or gamma) representation of the drop spectra and carries a total of four prognostic variables (mass and number of drops for each of the cloud and drizzle/rain spectra). A constant breadth is assumed for each of the spectra. The new approach differs from other parameterizations that use basis functions in that it accounts for the detailed bin interactions for collection and also allows for a differential (size-dependent) sedimentation. Efficiency is enhanced through the use of look-up tables that are prepared once, at the beginning of a simulation.

For autoconversion and collection, 36 bins are employed to represent the entire liquid water spectrum, where each successive bin represents a doubling of droplet mass from the previous bin. The mass and number transfer rates are accessed from a table in order to make the parameterization computationally efficient. The scheme, thus, combines the accuracy of a full bin computation with the computational speed of a bulk approach. For sedimentation, 50 bins are used to represent different sizes from the hydrometeor spectrum. As done for autoconversion and collection, a mapping is computed before the model run for the necessary range of parameter space which includes hydrometeor mean size, atmospheric density (which affects fall velocity), and grid cell where the hydrometeors fall from on the given time-step. These values are entered into a table and efficiently accessed during a model run.

2.4 Future implementation of Level 3.5

Use of bins to pre-compute collection parameters are being extended to ice categories. The major requirement for this development is defining appropriate kernels for collision efficiencies between cloud droplets and the various forms of ice. The efficiencies are known to be a strong function of cloud droplet diameter, as well as ice diameter and shape.

2.5 Coupled radiation parameterization

Coupled to the two-moment microphysical model is a flexible two-stream radiative transfer model which includes the effect of gaseous absorption by H2O, CO2, and O3. The model has 3 solar and 5 infrared bands; cloud optical properties are computed for each of these bands depending upon the level of the microphysical model. Water drop computations utilize Lorenz-Mie theory, while for various habit ice crystals we use a method for non-spherical particles described by Mitchell and Arnott (1994) and Mitchell (1997). Further development is needed here on the ice scattering and absorbing properties since we are not exactly sure how well these scattering and absorbing coefficients describe true ice properties.

Coupling to aerosol scattering and absorbing properties will require data describing the optical properties of various aerosol for comparisons. Parameterization of the aerosol optical properties will be more difficult than parameterization of water and ice optical properties because of the diversity of aerosol composition and the effects of aerosol delequesence.

3. Numerical Weather Prediction with Dynamically-active Aerosol

As can be seen from above we are getting very close to being operational with a model capable of realtime forecasting that includes direct activation of cloud droplets from CCN. Existing versions of RAMS and other bulk microphysics models simply input fixed concentrations of cloud droplets. CCN spectra are not used directly in those models. In future versions of RAMS, however, an important input parameter is the spectra of CCN. Thus, in forecast models in which the model domain covers coastal regions, continental interiors, and polluted boundary layers, it will be necessary to introduce the concentrations of CCN as a model forecast parameter. The model will have to be able to predict the local variations in CCN concentrations due to vertical and horizontal advection, and local sources and sinks of CCN due to microphysics and local sources. We refer to a model which predicts the sources and sinks of aerosol including their advection as a model with "dynamically-active aerosol."

In the dynamically-active aerosol model the values of C and k are diagnosed each timestep on each grid cell based on the number, size distribution, and chemistry of the hygroscopic aerosol present. Any number of chemical types and size distributions of hygroscopic aerosol may be prognosed in the model, but it is planned to use three categories as a standard. Prognosis of these categories will include advection, turbulent diffusion, natural and anthropogenic source terms, and sinks such as nucleation and precipitation scavenging. Accurate prediction of hygroscopic aerosol will require defining the locations and strengths of standard aerosol sources, plus typical or currently observed background aerosol concentrations.

In addition to CCN, we are also concerned about the concentrations of ice nuclei (IN) and their spatial and temporal variability. This is a much more challenging problem, because we suspect that IN spectra vary depending on the mode of activation (i.e., deposition/condensation-freezing nucleation vs. contact nucleation vs. immersion freezing). Moreover, estimating sources of IN is much more difficult than for CCN. Also, in the upper troposphere, we are interested in concentrations of haze particles that can serve as sites for homogeneous freezing. The haze particles may require an additional category of aerosol than needed for just CCN activation.

We should also keep in mind that the concentration of CCN does not provide complete information about the potential of a cloud to produce rain by collision and coalescence. Numerous studies over the years (Hindman, 1978; Johnson, 1976, 1982; Hobbs et al., 1977, 1978); Mather, 1991) have suggested that giant and ultra-giant aerosol particles can greatly enhance warm-rain production. Cooper et al. (1997) calculated that large concentrations of 1μm particles can accelerate the formation of drizzle-sized drops, which can have significant effects on both warm-rain formation and precipitation processes in supercooled clouds.

4. Data Needs of a Dynamically-active Aerosol/microphysics NWP Model

Once forecast models have opened up "Pandora's box" of dynamically-active aerosol, we then need to address how to measure these particles over the region covered by the forecast model. This is indeed a very challenging task since there are no routine measurements of CCN, haze particles, and IN. How then can we initialize a forecast model with dynamically-active aerosol?

It seems unlikely that any national weather service will introduce routine soundings of CCN and IN. Certainly a balloon-born disposable CCN/IN sensor does not appear to be on the horizon. We may be able to make use of some more or less climatological estimates of CCN and IN sources for various regions over the forecast area. This is possible over the oceans and certain land areas and may be possible over certain urban centers. A trial and error process of "parameterizing" sources of CCN and IN maybe required. Certainly a larger database of even occasional measurements of CCN and IN is needed for such a calibration.

Measurements of CCN spectra with a system such as Hudson's (1989) and IN with continuous flow diffusion chambers such as that developed by Rogers (1988) at various locations and throughout the troposphere are needed. But there are only a few of these systems operational, and their use is limited to a few field campaigns. Perhaps a CCN/IN processing center should be set up in which filter processing of IN such as Rosinski and Morgan's (1988) scheme be used for IN and an analogous CCN filter processing system be developed. In this way CCN and IN soundings and measurements at various locations and times could be sampled on prepared filters and then sent into the filter-processing center. This could expand the database for CCN climatology.

We have also considered the possibility of retrieving CCN (IN?) from remote sensors. This has the advantage of being able to provide long term monitoring of CCN at various locations and heights without the intensive manpower and costs of aircraft and balloon measurements.

4.1 Retrieving cloud condensation nucleus properties from Doppler cloud radar, microwave radiometer, and lidar

We have explored the possibility of using K_a-band Doppler radar, microwave radiometer, and lidar as a means of retrieving cloud condensation nucleus (CCN) properties in the stratocumulus-capped marine boundary layer. The retrieval is based on the intimate relationship between the cloud drop number concentration, the vertical air motion at cloud base, and the CCN activation spectrum parameters. The CCN properties that are sought are the C and k parameters in the $N=CS_k$ relationship, or alternatively, lognormal size (r_g) and number concentration (N_t) parameters of the accumulation mode. Cloud droplet concentration at cloud base is retrieved from a Doppler cloud radar combined with a microwave radiometer following a previously published technique (Frisch et al., 1995). Cloud base is determined from a lidar or ceilometer. Vertical velocity just above cloud base is determined from the vertically-pointing Doppler cloud radar, or by a Doppler lidar. By combining the retrievals of drop number, and vertical velocity, and assuming theoretical relationships between these parameters and the aerosol parameters, the C (or N_t) parameter can be derived. If a calibrated backscatter lidar measurement is available, a further iteration enables retrieval of both C and k, or N_t and r_g parameters. The retrieval has been demonstrated for a data set acquired during the ASTEX experiment. Figure 1 shows values of C and k parameters retrieved over the course of two hours on the morning of June 22, 1992 on the island of Porto Santo. Measurements are characterized by a good deal of variability in C but a fairly robust k on the order of 2.5. Although no collocated in-situ CCN measurements are available, a nearby overflight of the region by the UK C-130 plane indicated a continental airmass with several very distinct haze layers and very sharp concentration transitions (100/cc -2000/cc). The measured CCN parameters were C=1390; k=1.3. Retrieved C values are therefore not inconsistent, although retrieved k values are somewhat larger. Clearly, further validation of the proposed technique against in-situ measurements is required.

5. Cloud-scale Updrafts and Downdrafts Versus Model-resolved Velocities

Cloud microphysics models of greater and greater sophistication are being implemented in forecast and climate models ranging from mesoscale model grid spacing of a few tens of kilometers to general circulation models of 100 km or so, to single-column turbulent closure models. The magnitude of vertical motions explicitly resolved by these models range from a few tens of centimeters per second to one centimeter per second, to zero, respectively. These microphysics models are being applied to the simulation of cirrus clouds, middle tropospheric stratus clouds, boundary layer stratocumuli, and fogs where actual cloud-scale vertical velocities that drive cloud microphysics processes are 0.5 to a few meters per second.

Stevens et al. (1997) examined some of the implications of such a mismatch between model-resolved cloud forcing and actual cloud-scale velocity forcing. In a model with explicit supersaturations, such a mismatch ignores subgrid scale correlations in the aerosol-mass spectrum and the supersaturation spectrum, which are responsible for activating cloud drops near cloud base and determine the concentrations of activated cloud drops. Moreover, subgrid scale correlations in the collection equation are ignored which may significantly retard the initial growth of drizzle drops.

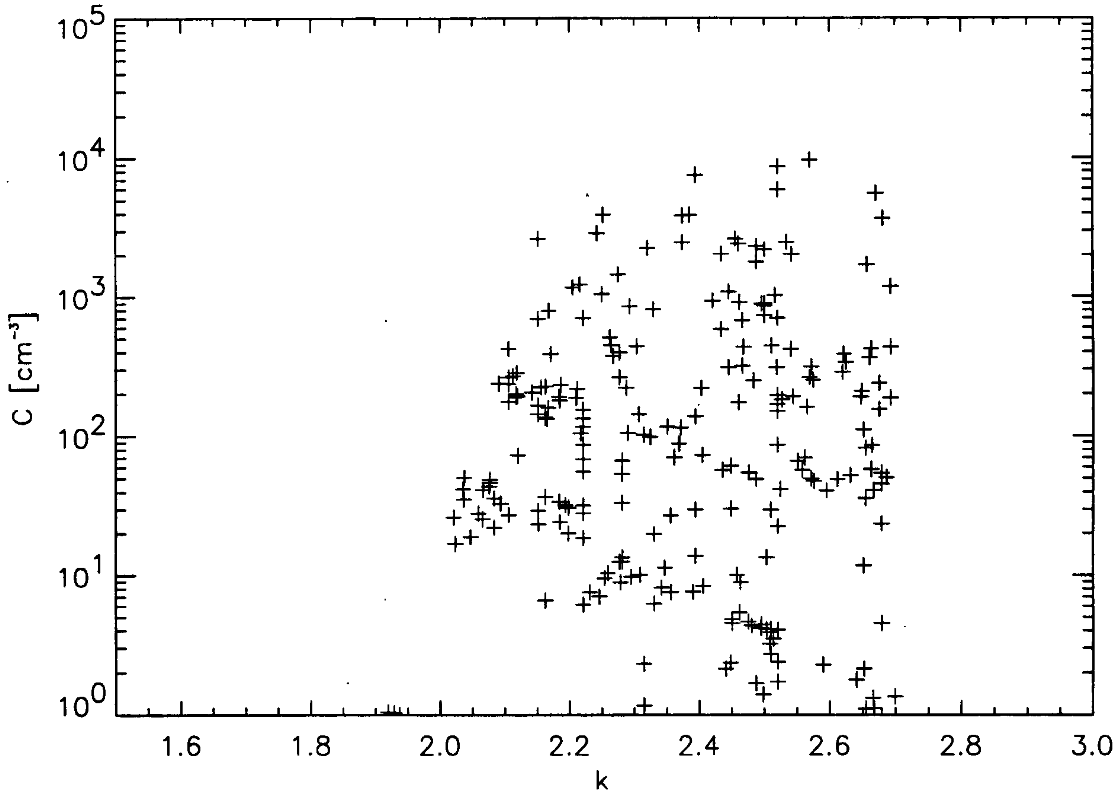

Figure 1. *C and k values for an activation spectrum $N=CS^k$ retrieved from cloud radar, lidar, and radiometer data during the ASTEX experiment.*

The mismatch in velocity scales in large-scale models also effects the residence times of cloud hydrometeors in cloud, which effects the overall growth of hydrometeors, and the tendency for size-sorting such that small droplets ascend in moderate intensity updrafts and larger drops settle through the cloud.

These mismatches in velocity scales effect the optical properties of clouds, their precipitation rates, and cloud diabatic heating. What is needed is to develop parameterizations that either implicitly or explicitly introduce cloud-scale vertical motions (or their effects) in large-scale models containing explicit representations of cloud microphysics.

6. Measurements Needed to Verify and Refine a Dynamically-active Aerosol/microphysics Model

As seen from above, a dynamically-active aerosol/microphysics model requires additional inputs over that for current forecast models. But what about verification of such a model? One could examine just the forecast products such as rainfall on the ground, or visibility, or icing and so forth. The problem is these products are the end result of a long-chain of physical processes as well as potential errors caused by intialization of base-state upper and surface meteorological data, ground soil moisture, vegetation coverage, sea surface temperatures, and the uncertainties of CCN and IN inputs. Thus if the model is in error it is nearly impossible to determine the sources of those errors.

In order to diagnose the fidelity of the dynamically-active aerosol/microphysics model and CCN/IN retrieval techniques, we need measurements of:

- aerosol size spectra and activity as CCN and IN
- cloud liquid water contents
- cloud droplet concentrations and size-spectra
- mixing ratios and concentrations of all relevant hydrometeor classes
- cloud-scale vertical velocities
- cloud supersaturations
- ice crystal habits
- cloud-scale radiative flux divergences

6. Summary

We have used RAMS physics and planned physics to be implemented in the next few years as a template for what can be expected in mesoscale forecast models in the not very distant future. Numerical weather prediction with dynamically-active aerosol/microphysics models is potentially just around the corner. These models require inputs of aerosol information in realtime that are currently not available nor even technically feasible to obtain today. Moreover, assessment of the fidelity of such models will require intensive field campaigns that measure a whole suite of microphysical parameters along with high-resolution upper-air and surface meteorological data.

The availability of such forecast models places quite a burden on the cloud microphysics measurement community.

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