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A hierarchical modeling study of the interactions among turbulence, cloud microphysics, and radiative transfer in the evolution of cirrus clouds

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Final Report

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Abstract:

This project used a hierarchy of cloud resolving models to address the following science issues of relevance to CRYSTAL-FACE:

- What ice crystal nucleation mechanisms are active in the different types of cirrus clouds in the Florida area and how do these different nucleation processes influence the evolution of the cloud system and the upper tropospheric humidity? How does the feedback between supersaturation and nucleation impact the evolution of the cloud?

- What is the relative importance of the large-scale vertical motion and the turbulent motions in the evolution of the crystal size spectra? How does the size spectra impact the life-cycle of the cloud, stratospheric dehydration, and cloud radiative forcing?

- What is the nature of the turbulence and waves in the upper troposphere generated by precipitating deep convective cloud systems? How do cirrus microphysical and optical properties vary with the small-scale dynamics? How do turbulence and waves in the upper troposphere influence the cross-tropopause mixing and stratospheric and upper tropospheric humidity?

The models used in this study were:

- 2-D hydrostatic model with explicit microphysics that can account for 30 size bins for both the droplet and crystal size spectra. Notably, a new ice crystal nucleation scheme has been incorporated into the model.

- Parcel model with explicit microphysics, for developing and evaluating microphysical parameterizations.

- Single column model for testing bulk microphysics parameterizations

Project Personnel

The PI, J. Curry, has moved from the University of Colorado to the Georgia Institute of Technology. She has requested that the grant be transferred to Georgia Tech.

V.I. Khvorostyanov (co-PI and project consultant) leads the theoretical microphysics research and is conducting the simulations using the cloud system model.

Hugh Morison is the graduate student working on the project. He developed a microphysics parameterization package suitable for large-scale models that is being tested on FIRE.ACE data and CRYSTAL data.

Research Highlights

Ice Nucleation

Theoretical work led by Khvorostyanov has led to new understanding of the heterogeneous ice nucleation process. We have developed expressions for nucleation in a polydisperse aerosol in the condensation-freezing and immersion modes, the threshold humidity and humidity of significant nucleation rate, dependence of the critical energy and nucleation rate on supersaturation, and temperature and humidity dependence of the aerosol radius with maximum contribution to nucleation rate. We have explained the critical temperature of spontaneous freezing as a function of solution molality and the critical saturation ratio for freezing. These new expressions for heterogeneous nucleation have been incorporated into a parcel model with explicit water and ice microphysics to simulate the process of ice nucleation under transient thermodynamic conditions. Simulations have been conducted over the temperature range -4 to $-70^\circ C$, with vertical velocities varying from 1 to 100 cm s^{-1}, for varying initial relative humidities and aerosol characteristics. It is shown that: a) the same cloud condensation nuclei (CCN) are responsible for the drop and crystal nucleation and can be identified as ice nuclei (IN) when crystals form; b) the nucleation rates and concentrations of nucleated crystals depend on temperature and supersaturation simultaneously; c) the new theory yields reasonable crystal concentrations over the entire temperature range for all tested initial conditions and vertical velocities; d) the kinetics of heterogeneous ice nucleation exhibits a negative feedback regulated via water supersaturation. This feedback is stronger than the corresponding feedback for drop nucleation, and explains discrepancies between observed ice nuclei concentrations and ice crystal concentrations without crystal multiplication mechanisms: very small fraction of CCN that may serve as IN, and much smaller crystal concentrations relative to drop concentrations. The relative importance of heterogeneous versus homogeneous nucleation was examined for a variety of cloud conditions. A comparison with chamber and field measurements shows general agreement. Based on these calculations, a simple parameterization for ice nucleation has been developed for use in bulk cloud models and large-scale models.

Feedback between ice nucleation and supersaturation.

The new heterogeneous ice nucleation formulation based on extended classical theory with simultaneous dependence on temperature and saturation ratio was applied to thin tropopause cirrus observed in CRYSTAL FACE. Simulations using homogeneous nucleation theory are able to produce comparable microphysical properties if the heterogeneous mode is turned off; hence, the homogeneous mode cannot be excluded in the domains with very small amounts of insoluble aerosol fractions. The calculated critical ice supersaturation for the onset of heterogeneous nucleation at these cold temperatures ($\sim 198 - 208$ K) was 70-80 % (for the assumed aerosol nucleation parameters), and 15-20 % higher for homogeneous nucleation. The calculated supersaturation relaxation time ranged from ~ 1-2 h in the center of the cloud to 3-6 h near the boundaries, which may explain the high values of ice supersaturation (30-80 %) observed in this cloud. Analysis of the supersaturation budget showed that supersaturation was generally non-equilibrium, and relaxation from the initial critical values to near equilibrium occurred only after several hours.

Bulk microphysics parameterization development

Led by Morison, a new double-moment microphysics parameterization for application in cloud and climate models has been developed that predicts the number concentrations and mixing ratios of four hydrometeor species (droplets, cloud ice, rain, snow. New physically based parameterizations are developed for simulating homogeneous and heterogeneous ice nucleation, droplet activation. and the spectral index (width) of the droplet size spectra. Two versions of the scheme are described: one for application in high-resolution cloud models and the other for simulating grid-scale cloudiness in larger-scale models. The versions differ in their treatment of the supersaturation field and droplet nucleation. For the high-resolution approach, droplet nucleation is calculated from Kohler theory applied to a distribution of aerosol that activates at a given supersaturation. The resolved supersaturation field and condensation/deposition rates are predicted using a semianalytic approximation to the three-phase (vapor. ice, liquid) supersaturation equation. For the large-scale version of the scheme, it is assumed that the supersaturation field is not resolved and thus droplet activation is parameterized as a function of the vertical velocity and diabatic cooling rate. The vertical velocity includes a subgrid component that is parameterized in terms of the eddy diffusivity and mixing length. Droplet condensation is calculated using a quasi-steady, saturation adjustment approach. Evaporation/deposition onto the other water species is given by nonsteady vapor diffusion allowing excess vapor density relative to ice saturation.

Evaluation of new bulk parameteration

FIRE.ACE. The new double-moment microphysics scheme wass implemented into a single-column model to simulate clouds and radiation observed during the period 1 April-15 May 1998 of the FIRE.ACE field projects. Mean predicted cloud boundaries and total cloud fraction compare reasonably well with observations. Cloud phase partitioning, which is crucial in determining the surface radiative fluxes, is fairly similar to ground-based retrievals. However, the fraction of time that liquid is present in the column is somewhat underpredicted, leading to small biases in the downwelling shortwave and longwave radiative fluxes at the surface. Results using the new scheme are compared to parallel simulations using other microphysics parameterizations of varying complexity. The predicted liquid water path and cloud phase is significantly improved using the new scheme relative to a single-moment parameterization predicting only the mixing ratio of the water species. Results indicate that a realistic treatment of cloud ice number concentration (prognosing rather than diagnosing) is needed to simulate arctic clouds. Sensitivity tests are also performed by varying the aerosol size, solubility, and number concentration to explore potential cloud-aerosol-radiation interactions in arctic stratus. *CRYSTAL-FACE:* The bulk model was able to simulate the 13 July 2002 CRYSTAL case and in particular the slow crystal growth and large supersaturation because of its detailed treatment of ice nucleation and supersaturation. The fraction of condensed ice relative to excess vapor predicted by both models was 40 – 60% for several hours, indicating that bulk models with zero supersaturation (instantaneous condensation of all excess vapor) would substantially over-predict the ice water path and optical thickness.

Publications:

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