Final report for the DOE ASR grant "Using Atmospheric Radiation Measurement (ARM) Observations to Validate and Improve Cloud Microphysical Schemes", grant number DE-FG02-08ER64574, PI: W. W. Grabowski

SUMMARY

In this project, we focused on applications of the new warm-rain and ice microphysics schemes to simulate various cloud systems. The overall goal was either to evaluate and improve specific aspects of the schemes (through comparisons with ARM/ASR observations) or to understand the coupling between aerosols, cloud microphysics and cloud dynamics in variety of situations. These studies are relevant to the indirect impact of atmospheric aerosols on climate. Below we report on selected key aspects of the research and then list all peer-reviewed papers that acknowledge support from this grant. Overall, studies partially supported by this grant resulted in 30 peer-reviewed publications (listed below), several dozens of conference presentations (including posters and oral presentations at the ASR Science Team Meetings), and two PhD dissertations. More detailed summaries of our accomplishments are included in yearly reports. Here we summarize only major efforts.

INTRODUCTION: THE NEW MICROPHYSICS SCHEMES

The double-moment warm-rain scheme is described in Morrison and Grabowski (JAS 2007 p. 2839-2861, and 2008 p. 792-812). The scheme includes relatively sophisticated representation of droplet activation, predicts supersaturation inside clouds (which implies that in-cloud activation of cloud droplets can now be predicted), and includes a novel approach to represent the entire range of subgrid-scale mixing scenarios for cloud microphysics (from the homogeneous mixing to the extremely inhomogeneous mixing). The new ice scheme, Morrison and Grabowski (JAS 2008 p. 1528-1548), moves away from the traditional approach of separating ice into different species (cloud ice, snow, graupel, hail) and instead diagnoses the ice particle characteristics using a prognostic rime mass fraction. The novel strategy was also used to develop a new ice bin microphysics scheme under funding from this grant (Morrison and Grabowski 2010).

ICE-FREE CLOUDS AND WARM-RAIN PROCESSES

The double-moment warm-rain scheme was applied in large-eddy simulations of shallow convection based on the nonprecipitating case (BOMEX; Barbados Oceanographic and Meteorological Experiment) as well on the precipitating case (RICO, Rain In Cumulus over the Ocean, http://www.knmi.nl/samenw/rico/). These studies involved two PhD students, jointly supervised by the PI and his colleague from the University of Warsaw (UW, Poland), Prof. Hanna Pawlowska. Joanna Slawinska defended her PhD thesis in early April 2011 and her key results are presented in a paper already published

(Slawinska et al. 2012). Model results documented an important impact of in-cloud CCN activation (i.e., activation above the cloud base) that is associated with entrainment and mixing of environmental air into shallow cumuli. The in-cloud activation was shown to have significant impact on mean optical properties of a shallow cumulus cloud field and appeared to be consistent with TWP ARM observations analyzed in McFarlane and Grabowski (2007). The homogeneity of subgrid-scale mixing appeared to have a smaller impact than in previous studies applying a single-moment microphysics. A follow-up study applying bin microphysics (Grabowski et al. 2011a) was reported in Wyszogrodzki et al. (2011) confirming previous results. Precipitation processes in shallow convection were studied in Grabowski et al. (2011b) and showed rather insignificant impact of rain on bulk properties of shallow convective clouds.

A novel subgrid scheme was also developed to locally predict the homogeneity of subgrid-scale mixing. The overall strategy was to combine the approach that predicts the progress of turbulent cloud-environment mixing with a parameterization of the homogeneity suggested by a large set of direct numerical simulations using bin-microphysics of microscale cloud-clear air mixing. Both of these methodologies were developed in our previous research. The novel approach was included in the large-eddy simulation model and model results are reported in Jarecka et al.~(2012). The key result is that differences between various mixing scenarios have even smaller effects when delay of evaporation is included. This is due to the fact that the air entrained into a convective cloud is often close to saturation because it comes from a narrow shell of moistened air from the cloud “halo”; differences between various subgrid-scale mixing scenarios are small when the cloud-free air is close to saturation. Ms. Jarecka is finalizing her dissertation; it will be submitted in spring 2012, with her PhD defense tentatively scheduled for summer 2012.

DEEP CONVECTION AND ICE MICROPHYSICS

Studies of various ice-bearing cloud systems, with the emphasis on the impact of atmospheric aerosols (CCN and IN), were conducted with support from this grant. They include idealized simulations of convective-radiative quasi-equilibrium, simulations of tropical deep convection observed in TWP-ICE field project, and simulations of polar clouds, including extensive comparisons with ARM observations.

An idealized study of indirect aerosol effects in convective-radiative quasi equilibrium (Grabowski and Morrison 2011) found a relatively small impact of aerosols on deep convection, in contrast to past suggestions based on heuristic arguments. A follow-up study applying large-scale forcing from TWP-ICE field project (Morrison and Grabowski 2011) quantified these effects further by applying a large-ensemble-simulation approach. In particular, the latter study suggests that the weak increase of cloud tops in polluted conditions, suggested by satellite observations and interpreted as a result of the so-called convective invigoration, may be simply a result of slower sedimentation of more numerous and smaller ice crystals that characterize upper parts of polluted clouds. Our TWP-ICE simulations were also included in the ARM/GCSS cloud-resolving model intercomparison (Fridlind et al. 2012). We are currently using the ensemble approach applied to TWP-ICE to explore how convective fluxes and the thermodynamic environment respond over time to perturbations in heating as a way to mimic aerosol impacts previously hypothesized from heuristic arguments, with results to be reported in a future publication. This study shows the existence of different timescales of the response, with relatively rapid adjustment of the environment minimizing the impact of this heating on the convective fluxes over timescales longer than 1-2 days. A study concerning effects of aerosols on supercell convection was reported in Morrison (2012). This study showed considerable sensitivity of aerosol effects on convective dynamics and surface precipitation with alterations to model formulations as well as small perturbations to initial conditions. It was concluded that improved generality and quantification of aerosol effects on deep convective storms is likely to require ensemble methods as well as improved model parameterizations.

Morrison has led activities within the GCSS (GEWEX Cloud System Study) Working Group on Polar Clouds (and continuing as a steering committee member of the GEWEX Global Atmospheric System Studies). As part of this effort, he co-led the ARM/GCSS MPACE model intercomparison study in 2008-2009 with Dr. Stephen Klein under previous ARM funding (Klein et al. 2009, QJRMS, p. 979-1002; Morrison et al. 2009, QJRMS, p. 1003-1019). In follow-up studies partially funded under this grant, he led a cloud model/LES intercomparison study of a case of shallow weakly-forced mixed-phase clouds observed during the SHEBA field experiment (Morrison et al. 2011a,b), and is currently collaborating with Dr. Mikhail Ovchinnikov and other ARM/ASR scientists on an intercomparison study based on ISDAC measurements. This study found that model solutions bifurcated into two distinct regimes consisting of either persistent mixed-phase clouds with large surface radiative forcing or thin all-ice clouds with little surface radiative forcing. A given model could produce either state with small changes in the concentration of heterogeneous ice nuclei, which are a small subset of aerosols that have the ability to form ice at temperatures warmer than -40 deg C. These results support the existence of two quasi-steady states for the given large-scale forcing conditions, which is consistent with recent observations in the central Arctic. The idea of bifurcated, resilient states emerging from the complex Arctic surface-cloud-atmospheric boundary layer system was further explored in a review/synthesis paper published in Nature Geoscience (Morrison et al. 2012a). In collaboration with other ARM/ASR scientists, Morrison was also involved in observational and modeling studies of clouds observed during MPACE (Solomon et al. 2009) and ISDAC (Solomon et al. 2011). These studies investigated interactions between cloud microphysics, radiation, and turbulence in mixed-phase boundary layer clouds, and in particular highlighted the role of humidity inversions at cloud top in helping to explain the resilience of these clouds.

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