Cloud Model Validation Using Particle Size & Ice Crystal Morphology Data Derived from M-PACE High Spectral Resolution Lidar & Millimeter Wavelength Radar

FINAL REPORT

Mixed-Phase Cloud Simulation/ARM Cloud Modeling Working Group Model Intercomparison:

Final simulations were submitted to the Atmospheric Radiation Measurement (ARM) program's Cloud Modeling Working Group and World Meteorological Organization M-PACE model intercomparison (Klein et al., 2009). Simulations from the University of Wisconsin Non-Hydrostatic Modeling System (UW-NMS) along with those from other models indicate a strong tendency to overproduce ice, resulting in a decimation of the liquid portion of mixed-phase stratus through the Bergeron-Findeissen process. Very few simulations were able to maintain the liquid layer throughout the simulation. Further investigation into causes of ice production in the UW-NMS, for both the Spectral Habit Ice Prediction System (SHIPS) and a more traditional bulk microphysics parameterization indicates an overproduction of ice through deposition nucleation.

Ice nucleation has been a longstanding problem in the correct simulation of cloud systems in freezing temperatures. One of the issues with deposition freezing controlling the ice-water balance in the M-PACE case is that there were very few free ice nuclei (IN) detected with the Continuous Flow Diffusion Chamber (CFDC), which would be necessary for a large amount of deposition freezing. Because of this, we began investigating the feasibility of other modes of nucleation that may match M-PACE observations more closely. Of particular interest have been immersion and condensation freezing.

Based on a lack of IN observed at Barrow, along with a correlation between upward vertical motion and the amount of ice produced, we proposed the idea of an active immersion freezing regime within these stratus layers (de Boer et al., 2009). In this theory liquid droplets that had formed on mixed aerosol particles, containing both soluble and insoluble material, grow to a size where the concentration of solution of a droplet is no longer inhibiting ice nucleation and therefore the droplet is allowed to freeze. This

solution effect requires model knowledge of aerosol type and composition, and is not usually incorporated in simulations due to the associated computational expense. However, Diehl and Wurzler (2004) incorporated this type of process into a model parameterization. Recently, we have included this parameterization into the UW-NMS, and found that simulations run with immersion freezing only, sustain liquid cloud layers for extended time periods. Because this process is self-limiting (ice forms after droplets have grown, halting further droplet growth), ice is not able to decimate the cloud layer as it does with other nucleation modes.

Simulations investigating the role of immersion freezing in mixed-phase Arctic stratus were completed under a new intercomparison framework (SHEBA, Morrison and Zuidema, 2008). These simulations were reviewed in a doctoral thesis completed partially under the funding supplied through this grant (de Boer, 2009). Immersion freezing was illustrated to be a major contributor to ice production within these cloud layers, and aerosol properties were illustrated to be an important consideration in the simulation of this process. In particular, the soluble mass fraction and aerosol insoluble mass type were demonstrated to influence simulation of the immersion freezing process, with low soluble mass fractions and insoluble mass types with high freezing efficiencies resulting in higher ice production.

Construction of a Ground-Based Validation Data Set:

As discussed in previous progress reports, data collected by the AHSRL and MMCR during the M-PACE period was analyzed in order to provide a statistical dataset for validation of simulations of mixed-phase stratus. 270 hours of single-layer cases were reviewed, and mean values for cloud base height, cloud thickness, cloud optical thickness, cloud temperature, wind direction, and liquid and ice particle size, particle number density, and water content were derived. Here, we provide a brief overview of the findings of this study. Additional details can be found in de Boer et al. (2009).

Single-layer mixed-phase clouds observed at Barrow during the fall of 2004 had a mean cloud base altitude of 688 m, and a mean thickness of ~650 m. They were observed at cloud-top temperatures ranging from 249-263 K. When compared with observations from Eureka, it becomes obvious that these mean characteristics vary significantly with location and season. Therefore, any simulation validation completed with this dataset should be done only for cases based specifically on the conditions observed at Barrow.

In addition to cloud macrophysical properties, data from the two instruments were

combined to derive a mean liquid particle size of 47 μm, a mean liquid number density of 2.8×10^4 L^{-1}, and mean total water content of 0.28 gm^{-3}. At the same time, ice precipitating from the cloud base had a mean effective diameter of 123 μm, a mean number density of 16 L^{-1}, and a mean water content of 0.03 gm^{-3}.

Generally, clouds observed at Barrow were found to be thicker, lower and containing higher water and ice contents than those observed at Eureka. This is likely due in part to the fact that these clouds were found to occur on a convective boundary layer during a "cold-air outbreak" type of situation, with wind conditions generally from the northeast, coming off of the ice sheet and over the open Beaufort Sea before reaching Barrow. More water is available due to the nearby open ocean, and stronger vertical motion is generated through boundary layer convection than would be generated by cloud-top radiative cooling.

As part of this evaluation, retrieval estimates were compared with in-situ measurements from aircraft operating during M-PACE. These results can be found in de Boer et al. (2008), and illustrate that the radar-lidar retrieval overestimates particle size of the liquid substantially, due to sensitivities of the individual instruments on the different peaks of the bimodal distribution of particles (liquid+ice). Similarly, the number density of liquid particles is underestimated, and the water content slightly overestimated.

For ice particles, retrieval errors stem largely from the ice particle shape assumed. For the one day of data from M-PACE utilized for comparison, different particle shape assumptions led to differences in particle effective diameter of up to 200 μm, number density of up to 90 L^{-1}, and water content of up to 0.011 gm^{-3}. However, limiting particle shape choices to reasonable shapes for the given scenario (i.e. not spheres) significantly reduces these ranges.

An attempt was made to derive a correlation between vertical motion and ice water content for the dataset reviewed above in order to confirm information presented by Shupe et al. Despite a visual correlation between the two variables, it proved difficult to derive a statistical correlation. This was mainly due to the computational cost of deriving vertical motion through the radar Doppler spectra as suggested in Shupe for the entire dataset. Because larger ice will have a faster fall speed, and since fall speed will dominate the Doppler velocity measurement, it is necessary to use an advanced technique such as the Doppler spectral analysis rather than simply using the measured Doppler velocity to derive such a correlation.

Final List of Publications Resulting from this Work:

Dissertations:

de Boer, G., An Improved Understanding of the Lifecycle of Mixed-Phase Stratiform Clouds Through Observations and Simulation, *PhD Thesis,* University of Wisconsin - Madison, Department of Atmospheric and Oceanic Sciences, May, 2009, 140 pp.

Journal Articles:

de Boer, G., T. Hashino and G.J. Tripoli, (2009), Sensitivity of Simulated Mixed-Phase Stratiform Cloud Properties to Aerosol Characteristics via Ice Nucleation in the Immersion Mode. *To be submitted to the Journal of Geophysical Research.*

de Boer, G., G.J. Tripoli and T. Hashino, (2009), A Theory for Ice Nucleation Through Immersion Freezing in Mixed-Phase Stratus. *In Review at Atmospheric Research.*

de Boer, G., E.W. Eloranta, (2009), Arctic Mixed-Phase Stratus Properties from Multiple Years of Surface-Based Measurements at Two High-Latitude Locations. *Accepted for publication in the Journal of Atmospheric Sciences.*

Morrison, H., R. McCoy, S. Klein, S. Xie, Y. Luo, A. Avramov, M. Chen, J. Cole, M. Falk, M. Foster, A. Del Genio, J. Harrington, C. Hoose, M. Khairoutdinov, V. Larson, X. Liu, G. McFarquhar, M. Poellot, K. von Zalzen, B. Shipway, M. Shupe, Y. Sud, D. Turner, D. Veron, G. Walker, Z. Wang, A. Wolf, K. Xu, F. Yang, G. Zhang, (2009), Intercomparison of Model Simulations of Mixed-Phase Clouds Observed During the ARM Mixed-Phase Arctic Cloud Experiment, Part II: Multi-Layered Cloud. *Accepted for publication in the Quarterly Journal of the Royal Meteorological Society.*

Klein, S.A., R. McCoy, H. Morrison, A. Ackerman, A. Avramov, G. de Boer, M. Chen, J. Cole, A.D. DelGenio, M. Falk, M. Foster, A. Fridlind, J.-C. Golaz, T. Hashino, J. Harrington, C. Hoose, M. Khairoutdinov, V. Larson, X. Liu, Y. Luo, G. McFarquhar, S. Menon, R. Neggers, S. Park, K. von Salzen, J.M. Schmidt, I. Sednev, B. Shipway, M. Shupe, D. Spangenberg, Y. Sud, D. Turner, D. Veron, G. Walker, Z. Wang, A. Wolf, S. Xie, K.-M. Xu, F. Yang, and G. Zhang, (2009), Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. Part I: Single layer cloud. *Accepted for publication in the Quarterly Journal of the Royal Meteorological Society*.

van Diedenhoven, B. , A. M. Fridlind , A. S. Ackerman , E. W. Eloranta ,G. M. McFarquhar, (2009), An evaluation of ice formation in large-eddy simulations of supercooled Arctic stratocumulus using ground-based lidar and cloud radar. *Accepted for publication in the Journal of Geophysical Research.*

de Boer, G., G.J. Tripoli, and E.W. Eloranta, (2008), Preliminary comparison of CloudSAT-derived microphysical quantities with ground-based measurements for mixed-phase cloud research in the Arctic**,** *Journal of Geophysical Research* **113**, D00A06, doi:10.1029/2008JD010029.

Shupe, M. D., P. Kollias, M. Poellot, and E. Eloranta, (2008), On Deriving vertical Air Motions from Cloud Radar Doppler Spectra, *Journal of Atmospheric & Oceanic Tech*nology **25**, 547-557.

Verlinde, J., J. Y. Harrington, G. M. McFarquhar, V. T. Yannuzzi, A. Avramov, S. Greenberg, N. Johnson, G. Zhang, M. R. Poellot, J. H. Mather, D. D. Turner, E. W. Eloranta, B. D. Zak, A. J. Prenni, J. S. Daniel, G. L. Kok, D. C. Tobin, R. Holz, K. Sassen, D. Spangenberg, P. Minnis, T. P. Tooman, M. D. Ivey, S. J. Richardson, C. P. Bahrmann, M. Shupe, P. J. DeMott, A. J. Heymsfield, and R. Schofield, (2007), The Mixed-Phase Arctic Cloud Experiment, *Bulletin of the American Meteorological Society,* **88**, 205-221.

Shupe, M. D., J. S. Daniel, G. deBoer, E. W. Eloranta, P. Kollias, E. Luke, C. N. Long, D. Turner, and J. Verlinde, (2008), A Focus on Mixed-Phase Clouds: The Status of Ground-Based Observational Methods, *Bulletin of the American Meteorological Society,* **89**, 1549-1562.

Conference Presentations:

de Boer, G., E. W. Eloranta, **Long Term Statistics of Mixed-Phase Arctic Stratus at Barrow and Eureka: Process Studies, Assessment of CloudSAT Detection, and Applications to Models**, 2008 *AGU Fall meeting*, Dec 15-19, 2008, San Fransico.

de Boer, G., T. Hashino, and G.J. Tripoli, **Effects of Immersion Freezing on Simulations of Mixed-Phase Stratus Clouds (Theory and Results)** *WMO International Cloud Modeling Workshop* July 13-17, 2008, Cozumel, Mexico.

de Boer, G. and E.W. Eloranta, **A Multi-Year Data-Set of Arctic Mixed-Phase Stratus Properties as Derived by a Combination of High-Spectral Resolution Lidar and Millimeter Cloud Radar** *24th International Laser Radar Conference* June 23-27, 2008, Boulder, Colorado.

de Boer, G., T. Hashino, G.J. Tripoli and E.W. Eloranta, **A Possible Role for Immersion Freezing in Mixed-Phase Stratus Clouds** *4th Pan-GCSS Meeting* June 2-6, 2008, Toulouse, France.

de Boer, G., E.W. Eloranta, T. Hashino, and G.J. Tripoli, **A Potential Role for Immersion Freezing in Arctic Mixed-Phase Stratus.** *ARM Science Team Meeting* March 10-14, 2008, Norfolk, VA.

de Boer, G., E.W. Eloranta, I.A. Razenkov, J.P. Hedrick, J.P. Garcia, and M.D. Shupe, **Long-Term Lidar and Radar Observations of Arctic Stratus at Two Locations.** *Annual Meeting of the American Meteorological Society* January 20-24, 2008, New Orleans, LA.

de Boer, G., E.W. Eloranta, and G.J. Tripoli. **Understanding Formation and Maintenance of Mixed-Phase Arctic Stratus Through Long-Term Observation at two Arctic Locations** *2007 Fall Meeting of the American Geophysical Union (AGU)*, December 10-14, San Francisco, CA.

de Boer, G., T. Hashino, G.J. Tripoli and E.W. Eloranta. **Studies Towards the Understanding of Ice Microphysics in Mixed-Phase Clouds,** *2007 International Union of Geophysics and Geodesy Meeting (IUGG)*, July 2-13, Perugia, Italy.

de Boer, G., E.W. Eloranta, G.J. Tripoli and T. Hashino. **Simulation and Observations of Mixed-Phase Arctic Stratus,** *2007 Atmospheric Radiation Measurement program Science Team Meeting*, March 26-30, Monterey, CA.

Eloranta, E. W., I. A. Razenkov, J. P. Garcia and J. Hedrick. **Particle Size Measurements Using Data from a High Spectral Resolution Lidar and a Millimeter Wavelength Radar,** *2007 Atmospheric Radiation Measurement program Science Team Meeting*, March 26-30, Monterey, CA.