Final Report – November 2018

Project Title: Aerosol effects on the anvil characteristics, cold pool forcing and stratiform-convective precipitation partitioning and latent heating of mesoscale convective systems

Project Number: DE-SC0010569

Program Manager: Shaima Nasiri

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Executive Summary

The overarching science goal of this project has been to assess the impacts of aerosols on mesoscale convective systems (MCSs). More specifically we have investigated the impacts of (a) aerosol types, (b) aerosol concentrations, and (c) the vertical and horizontal location of aerosols on the (1) anvil cloud characteristics and feedbacks; (2) total precipitation and the partitioning between convective and stratiform precipitation; (3) the vertical heating structure; (4) hydrometeor size distributions; and (5) the strength and intensity of the cold pools and updrafts. These have been achieved both through observational analyses and high-resolution cloud-resolving model simulations of three MCSs that were observed during the MC3E field campaign (25 April, 20 May and 23 May 2011).

The primary findings of these research are the following:

1. Condensation and deposition are the primary contributors to MCS latent warming, when compared to riming and nucleation processes. In terms of MCS latent cooling, sublimation, melting, and evaporation all play significant roles.
2. Throughout the MCS lifecycle, convective regions demonstrate an approximately linear decrease in the magnitudes of latent heating rates, while latent heating within stratiform regions is associated with transitions between MCS flow regimes including the rear inflow jet. Such information regarding the temporal evolution of latent heating within convective and stratiform MCS regions could be useful in developing parameterizations representing convective organization.
3. Increasing aerosol concentration from a clean continental to a highly polluted state produces an increase in the riming rates of cloud water, which results in less lofted cloud water in polluted environments. Aerosol-induced trends in the cloud mixing ratio profiles are, however, nonmonotonic in the mixed phase region, such that a moderate increase in aerosol concentration produces the greatest reduction in cloud water.
4. Less lofted cloud water due to enhanced riming rates leads to reduced anvil ice mixing ratios but to greater numbers of small ice crystals within the anvil. In spite of reduced anvil ice mixing ratio, the anvil clouds exhibit greater areal coverage, increased albedo, reduced cloud top cooling, and reduced net radiative flux, which produces an aerosol-induced warming (reduced cooling) effect in these MCSs.
5. Lower-tropospheric aerosol particles largely influence the MCS precipitation response directly rearward of the leading cold pool boundary. However, further backward in the MCS,

the relative impact of lower- versus mid-tropospheric aerosol particles is strongly dependent on the MCS structure and differences in the line-normal wind shear.

6. Mid-tropospheric aerosol particles are able to activate new cloud droplets in the mid-tropospheric levels of convective updrafts and thereby enhance mixed-phase precipitation through increased cloud riming.

Final Report

The overarching science goal of this project has been to assess the impacts of aerosols on mesoscale convective systems (MCSs). More specifically we have investigated the impacts of (a) aerosol types, (b) aerosol concentrations, and (c) the vertical and horizontal location of aerosols on the (1) anvil cloud characteristics and feedbacks; (2) total precipitation and the partitioning between convective and stratiform precipitation; (3) the vertical heating structure; (4) hydrometeor size distributions; and (5) the strength and intensity of the cold pools and updrafts. These have been achieved both through observational analyses and high-resolution cloud-resolving model simulations of three MCSs that were observed during the MC3E field campaign (25 April, 20 May and 23 May 2011).

The results arising from this project have been disseminated in 3 published papers, an additional paper soon to be submitted for review, and 20 conference presentations, 9 of which were invited.

The project supported the M.S. degree of Peter Marinescu at Colorado State Univeristy, as well as the start of his Ph.D. research. Peter graduated with his M.S. degree in Spring 2016. Furthermore, a summer intern, Rachel Phinney, got to work in the van den Heever group in the summer of 2016. She conducted research using Peter's simulations and presented two conference talks on her internship research.

Research Highlights

1. The Evolution of Latent Heating Profiles in MCSs and the Role Played by Microphysics

Previous studies have shown that the shapes and magnitudes of latent heating profiles have been are different within the convective and stratiform regions of mesoscale convective systems (MCSs). Properly representing these distinctions has significant implications for the atmospheric responses to latent heating on various scales. This study examined (1) the microphysical process contributions to latent heating profiles within MCS convective, stratiform, and anvil regions and (2) the time evolution of these profiles throughout the MCS lifetime, using cloud-resolving model simulations. Simulations of two MCS events that were observed during the Midlatitude Continental Convective Clouds Experiment (MC3E) were conducted. Several features of the simulated MCSs were compared to a suite of observations obtained during the MC3E field campaign, and we found that the simulations reasonably reproduced the MCS events.

Analysis of the simulations demonstrated that condensation and deposition are the primary contributors to MCS latent warming, when compared to riming and nucleation processes. In terms of MCS latent cooling, sublimation, melting, and evaporation all play significant roles. These results are summarized in Figure 1. It is evident that throughout the MCS lifecycle, convective regions demonstrate an approximately linear decrease in the magnitudes of latent

heating rates, while latent heating within stratiform regions is associated with transitions between MCS flow regimes as shown in Figure 2. Such information regarding the temporal evolution of latent heating within convective and stratiform MCS regions could be useful in developing parameterizations representing convective organization.

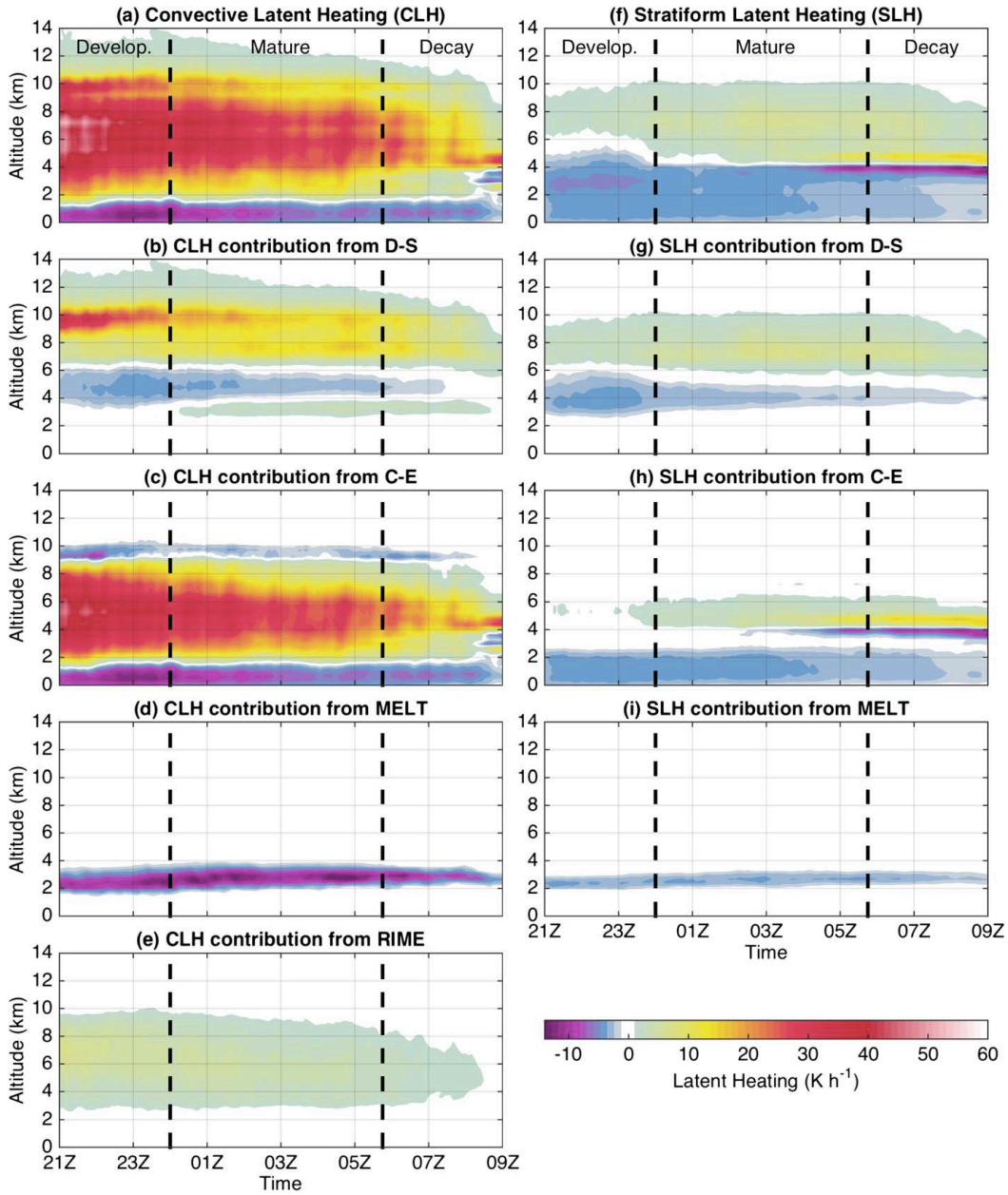

Figure 1: The evolution of latent heating rates and contributing microphysical processes for convective and stratiform regions for the 23–24 May event. (a) CONV latent heating and (b–e) contributions from key microphysical processes are shown throughout the 12 h analysis period. The evolution of STRA latent heating and contributions from key microphysical processes are shown in Figures 10f–10i. In STRA regions, RIME processes are negligible and are therefore not shown. Approximate transitions between the development, mature, and decay stages are shown with the dashed, black lines (after Marinescu et al 2016).

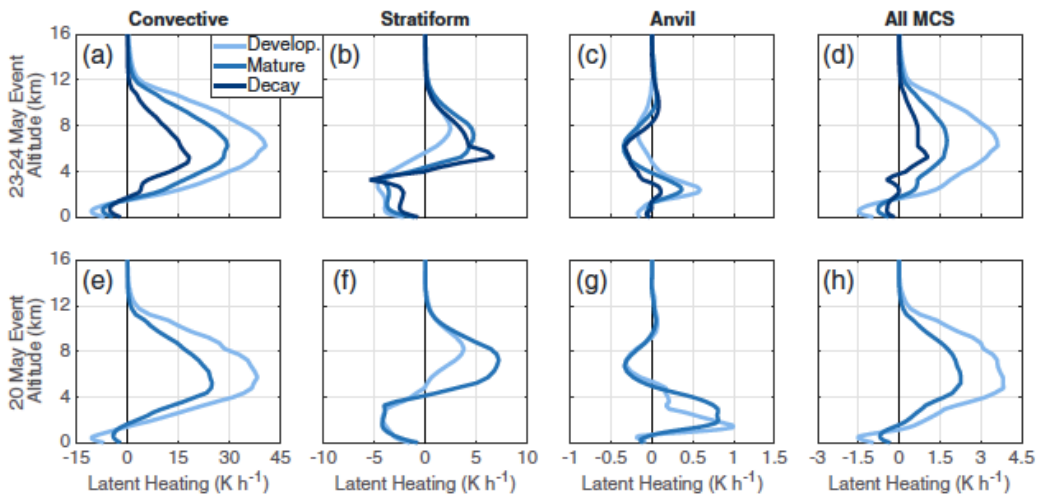

Figure 2: Schematic of the latent heating profile changes with MCS evolution. Profiles are shown for CONV, STRA, and ANVL regions, as well as the entire MCS. Profiles were calculated for both (a–d) the 23–24 May event and (e–h) the 20 May event and were smoothed using a 5-point moving average. The decay stage for the 20 May event is not shown since new, developing convection formed during this event's decay stage (after Marinescu et al 2016).

These results were published in the following manuscript:

- Marinescu, P.J., S.C. van den Heever, S.M. Saleeby and S.M. Kreidenweis, 2016: The microphysical contributions to and evolution of latent heating profiles in two MC3E MCSs. *J. Geophys. Res.,* **121**, 7913–7935.

2. Aerosol Impacts on the Anvil Characteristics of MCSs

The microphysical characteristics, along with the spatial length scales of convective anvils play a critical role in cloud-radiative forcing and hence in Earth's energy budget. In this study, a suite of simulations of two mesoscale convective systems (MCSs) that occurred during the Midlatitude Continental Convective Clouds Experiment were performed in order to examine the impact of aerosol number concentration on the vertical distributions of liquid and ice condensate and the macrophysical, microphysical, and radiative properties of the deep convective cirrus anvils.

Analyses of the simulations suggest that increasing aerosol concentration from a clean continental to a highly polluted state produces an increase in the riming rates of cloud water, which resulted in less lofted cloud water in polluted environments. Aerosol-induced trends in the cloud mixing ratio profiles were, however, nonmonotonic in the mixed phase region, such that a moderate increase in aerosol concentration produced the greatest reduction in cloud water. Generally, less lofted cloud water led to reduced anvil ice mixing ratios but to greater numbers of small ice crystals within the anvil (Figure 3). In spite of reduced anvil ice mixing ratio, the anvil clouds exhibited greater areal coverage, increased albedo, reduced cloud top cooling, and

reduced net radiative flux, which produced an aerosol-induced warming (reduced cooling) effect in these MCSs (Figure 4).

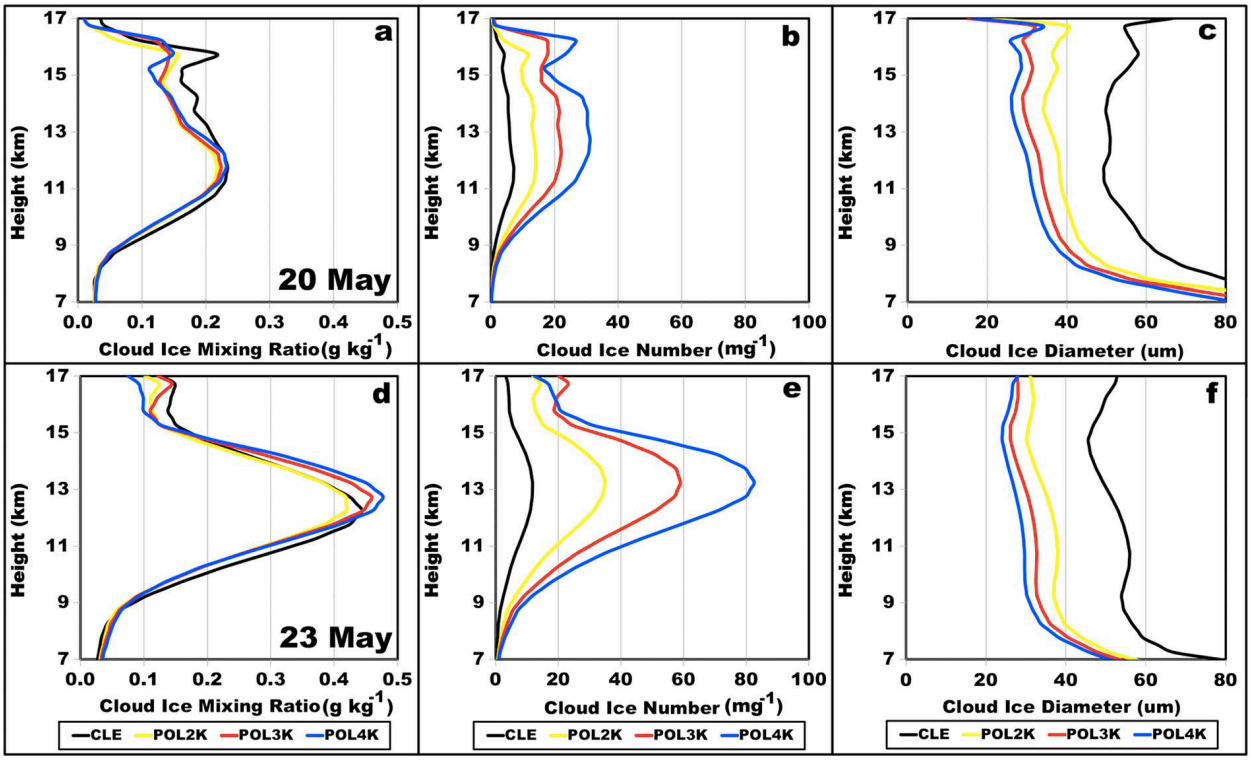

Figure 3: (a, d) Cloud ice mixing ratio (g kg^{-1}), (b, e) number concentration (mg^{-1}), and (c, f) mean diameter (μm) for the 20 May (Figures 8a–8c) and 23 May (Figures 8d–8f) cases (after Saleeby et al 2016)

The results of this work have been presented in the following publication:

- Saleeby, S.M., S.C. van den Heever, P.J. Marinescu, S.M. Kreidenweis, and P.J. DeMott, 2016: Aerosol indirect effects on the anvil characteristics of mesoscale convective systems. *J. Geophys. Res.*, **121**, 10,880-10,901.

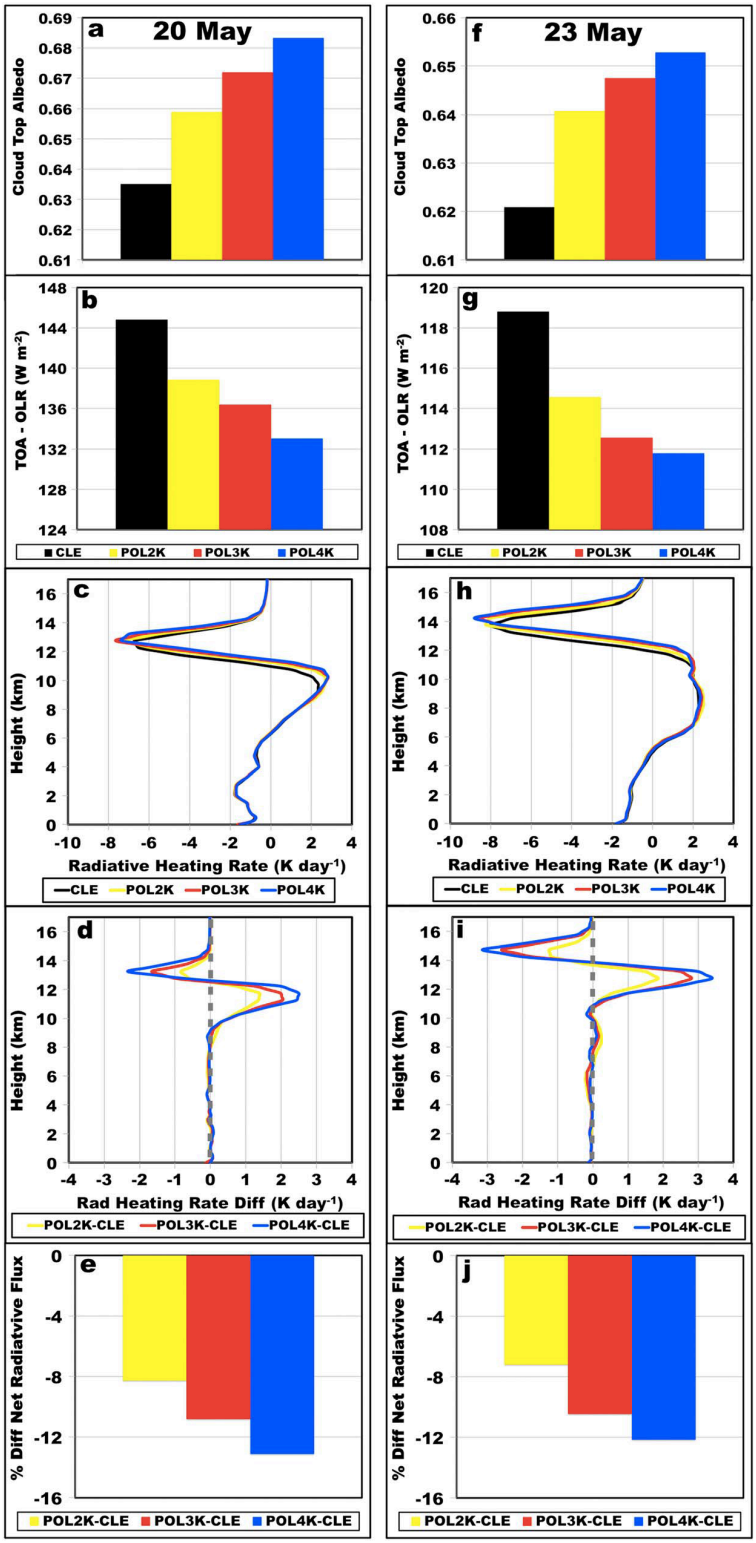

Figure 4: (a, f) Cloud top albedo (fraction), (b, g) TOA-OLR (Wm^{-2}), (c, h) radiative heating rate ($K\ d^{-1}$), (d, i) difference in radiative heating rate ($K\ d^{-1}$), and (e, j) percent change in net column radiative flux for the 20 May (Figures 10a–10e) and 23 May (Figures 10f–10j) cases (after Saleeby et al 2016).

3. The Relative Roles of Lower- and Mid-Tropospheric Aerosols on MCS Precipitation

In this element of the project, simulations of two leading-line, trailing-stratiform mesoscale convective system (MCS) events that occurred during the Midlatitude Continental Convective Clouds Experiment (MC3E) were used in order to understand the relative microphysical impacts of lower- versus mid-tropospheric aerosol particles (APs) on MCS precipitation. For each MCS event, four simulations were conducted in which the initial vertical location and concentrations of cloud droplet nucleating APs were varied. These simulations were used to determine the precipitation response to AP vertical location. It is important to note that the total integrated number and mass of the initial aerosol profiles used in the sensitivity simulations remained constant, so that differences between the simulations could be directly attributable to changes in the vertical location of cloud droplet nucleating APs as opposed to changes in total number concentrations.

Analysis of the simulations demonstrated that lower-tropospheric APs largely influenced the MCS precipitation response directly rearward of the leading cold pool boundary. However, further backward in the MCS, the relative impact of lower- versus mid-tropospheric APs is strongly dependent on the MCS structure, which varied between the two events because of differences in line-normal wind shear. Mid-tropospheric APs were able to activate new cloud droplets in the mid-tropospheric levels of convective updrafts and thereby enhance mixed-phase precipitation through increased cloud riming. This microphysical pathway had a more significant impact on mixed phase precipitation in the storm experiencing weaker line-normal wind shear conditions. These results, which are summarized in the schematic in Figure 5, expose the importance of properly representing mid-tropospheric APs when assessing aerosol effects on clouds. The utility and importance of assessing aerosol effects within the different regions of MCSs was also demonstrated.

These results are described in the following paper:

- Marinescu, P.J., S.C. van den Heever, S.M. Saleeby, S.M. Kreidenweis, and P.J. DeMott, 2017: The microphysical roles of lower-tropospheric versus midtropospheric aerosol particles in mature-stage MCS precipitation. *J. Atmos. Sci.*, **74**, 3657-3678.

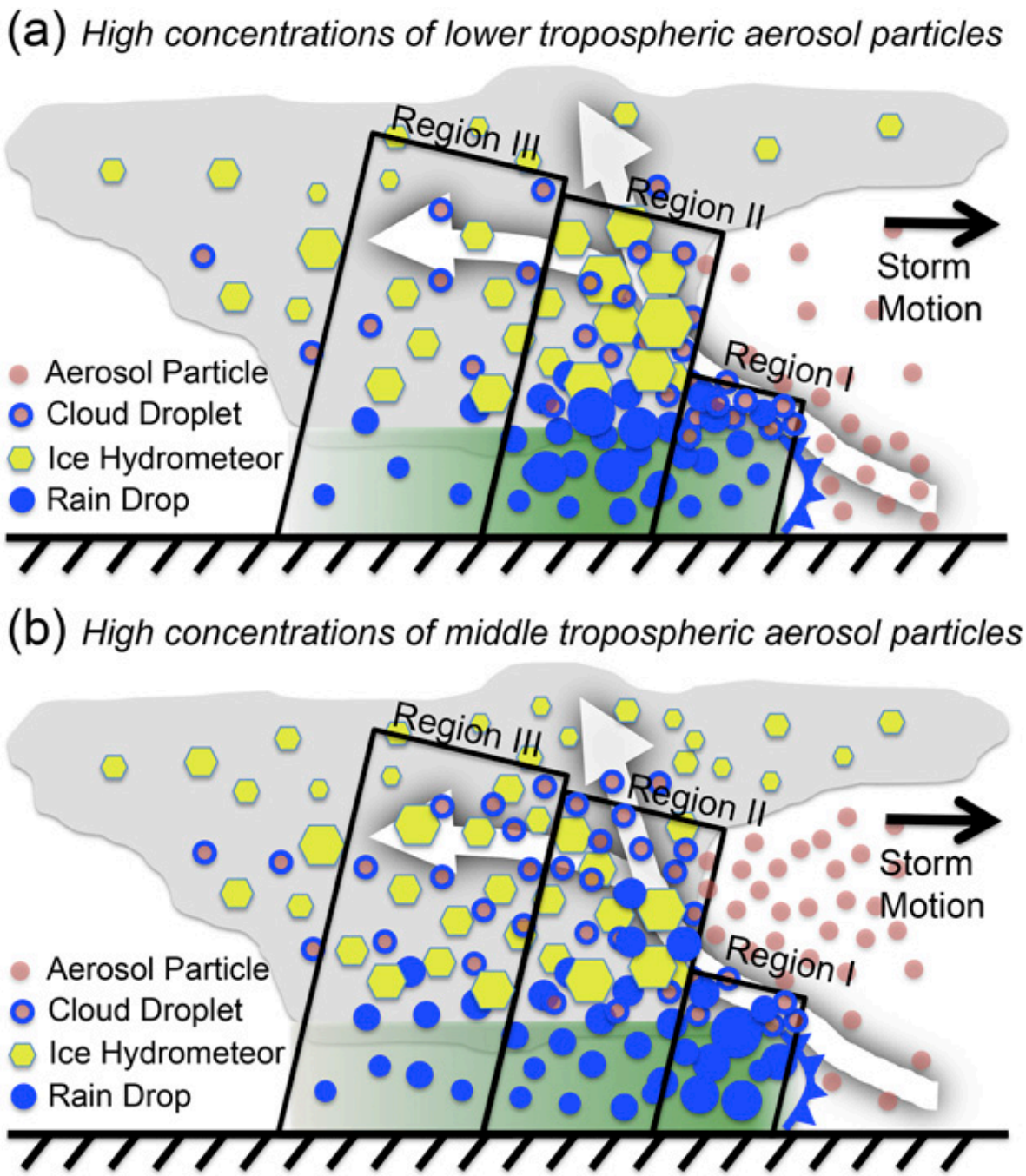

Figure 5: Schematic of an LLTS MCS under high concentrations of (a) LT and (b) MT APs. The gray area represents cloudy regions, while the green shading represents rainfall with darker shading depicting heavier rain. The blue frontal symbols represent the leading cold pool boundary, and the white arrows represent the primary front-to-rear ascending flow. The three boxes represent three different precipitation regions of the MCS where different microphysical processes are governing the precipitation. Particle types are specified in the legends, with the amounts and sizes of hydrometeors representative of the relative concentrations and mean diameters of particles within those regions (after Marinescu et al 2017).

Published Papers

- Marinescu, P.J., S.C. van den Heever, S.M. Saleeby and S.M. Kreidenweis, 2016: The microphysical contributions to and evolution of latent heating profiles in two MC3E MCSs. *J. Geophys. Res.,* **121**, 7913–7935.
- Saleeby, S.M., S.C. van den Heever, P.J. Marinescu, S.M. Kreidenweis, and P.J. DeMott, 2016: Aerosol indirect effects on the anvil characteristics of mesoscale convective systems. *J. Geophys. Res*., **121**, 10,880-10,901.
- Marinescu, P.J., S.C. van den Heever, S.M. Saleeby, S.M. Kreidenweis, and P.J. DeMott, 2017: The microphysical roles of lower-tropospheric versus midtropospheric aerosol particles in mature-stage MCS precipitation. *J. Atmos. Sci.*, **74**, 3657-3678.

Papers in Preparation

- Marinescu, P.J., Ezra J. T. Levin, Don Collins, Sonia M. Kreidenweis, and Susan C van den Heever, 2018: Quantifying the cycles of aerosol number concentrations and its seasonal variability in the Southern Great Plains. To be submitted to ACP.

Note: while the work on this quantification of aerosol characteristics over the SGP site began on this funding award, it has continued on Sonia Kreidenweis' most recent ASR funded project. When published both funding awards will be acknowledged.

Conference Presentations

- van den Heever, S.C., 2017: Aerosols, cloud physics and radiation. C-RITE Workshop, NCAR, 22-24 May 2017, Boulder, CO (Keynote talk)
- van den Heever, S.C., 2017: An Observational Wish List for the Evaluation of Microphysical and Dynamical Processes within Cloud Resolving Models. 97th American Meteorological Society Annual Meeting, AMS, 22-26 January 2017, Seattle, WA (Invited)
- Phinney, R., P.J. Marinescu and S.C. van den Heever, 2017: Quantifying the transport of air into mesoscale convective systems. 97th American Meteorological Society Annual Meeting, AMS, 22-26 January 2017, Seattle, WA (Poster)
- Marinescu, P.J., S.C. van den Heever, S. M. Saleeby, and S.M. Kreidenweis, 2017: The evolution of latent heating within two mesoscale convective systems and a simple parameterization scheme. 97th American Meteorological Society Annual Meeting, AMS, 22-26 January 2017, Seattle, WA (Poster)
- van den Heever, S.C., 2016: The ingestion and transport of aerosols by convective storms. Telluride Summer Research Centre (TSRC) Workshop "Aerosols and Clouds: Connections from the Laboratory to the Field to the Globe", 27 June – 1 July 2016, Telluride, Colorado (Invited)
- van den Heever, S.C., P.J. Marinescu, S.M. Saleeby, P.J. DeMott and S.M. Kreidenweis, 2016: Latent heating, microphysical and aerosol processes of MC3E mesoscale convective systems. ARM/ASR Joint User Facility and PI Meeting, DOE, 2-5 May 2016, Tyson's Corner, VA. (Keynote; given by Sonia Kreidenweis)
- Marinescu, P.J., S.C. van den Heever, S.M. Saleeby, S.M. Kreidenweis, and P.J. Demott, 2016: Impacts of elevated aerosol layers on MCS precipitation and cold pools. 96th American Meteorological Society Annual Meeting, AMS, 10-14 January 2016, New Orleans, LA (Oral)
- Phinney, R., P.J. Marinescu and S.C. van den Heever, 2016: Quantifying the transport of air into mesoscale convective systems. AGU Fall Meeting, 12-16 December 2016, San Francisco, CA (P).
- van den Heever, S.C., 2015: Environmental modulation of aerosol impacts on convective storms.

MASS Seminar, MIT, 11 May 2015, Boston, MA (Seminar)

- Marinescu, P.J., S.M. Saleeby, S.C. van den Heever, and S.M. Kreidenweis, 2015: The evolution of latent heating within two MC3E mesoscale convective systems. AGU Fall Meeting, 14-18 December 2015, San Francisco, CA. (Poster)
- Saleeby, S.M., S.C. van den Heever, P.J. Marinescu, S.M. Kreidenweis, P.J. Demott, W.-K. Tao, T. Matsui, and D. Wu, 2015: Understanding the role of riming in deep convection through variability in collection efficiency and aerosol effects. AGU Fall Meeting, 14-18 December 2015, San Francisco, CA. (Poster)
- van den Heever, S.C., P. Stier, W.-K., Tao, L.D. Grant, S.R. Herbener, P.J. Marinescu, S.M. Saleeby, and A.M. Sheffield, 2015, The Modulation of Aerosol Impacts on Convective Clouds and Precipitation, Earth Observations for Water Cycle Science 2015, ESA-GEWEX, 20-23 October 2015, Frascati, Italy (Invited)
- Marinescu, P.J., S.M. Saleeby, S.C. van den Heever, S.M. Kreidenweis, and P.J. DeMott, 2015: Impacts of Aerosol Vertical Location and Concentration on MCS Convective and Stratiform Regions. 95th American Meteorological Society Annual Meeting, AMS, 4-8 January 2015, Phoenix, AZ. (Oral).
- Kreidenweis, S.M., P.J. Marinescu, S.M. Saleeby, P.J. DeMott, and S.C. van den Heever, 2015: Modeling Aerosol Impacts on MC3E MCSs. Center for Multiscale Modeling of Atmospheric Processes 2015 Summer Meeting, Fort Collins, CO. (Oral)
- Kreidenweis, S.M., P.J. Marinescu, S.C. van den Heever, A. Jefferson, C. Kuang, J. Wang and D. Collins, 2015: Characterization of the aerosol environment in spring 2011 during the Midlatitude Continental Convective Clouds Experiment (MC3E). 95th American Meteorological Society Annual Meeting, Phoenix, AZ. (Poster)
- van den Heever, S.C., 2014: Aerosol Impacts on the Microphysical and Dynamical Characteristics of Convective Storms. Atmospheric, Oceanic and Planetary Seminars, 16 October 2014, Oxford University, Oxford, England (Seminar)
- van den Heever, S.C., 2014: Environmental modulation of aerosol impacts on convective storms. TSRC Aerosols and Clouds: Connections from the Laboratory to the Field to the Globe, 4-8 August 2014, Telluride, CO (Invited)
- van den Heever, S.C., S.M. Saleeby, P. Marinescu, S.M. Kreidenweis and P.J. DeMott, 2014: Aerosol Impacts on MC3E Case Studies, Plenary talk at the DOE-ASR P.I. Spring Meeting, 10-14 March 2014, Washington D.C (Invited)
- Saleeby, S.M., S.C. van den Heever, P.J. Marinescu, S.M. Kreidenweis and P.J. Demot, 2014: Mesoscale Convective System Anvil Cloud Response to Aerosol Loading. AGU Fall Meeting, 15-19 December 2014, San Francisco, CA. (Oral)
- van den Heever, S.C., 2013: Simulations of MCS development during MC3E, ASR Fall Working Group Meeting, 4-8 November 2013, Rockville, MD.