Aerosols, Cloud Physics and Radiation

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Convective Storm Processes

- Accurately predicting convective storm PROCESSES remains very challenging – in part due to non-linear feedbacks
- There are many aerosol, microphysical and radiative processes and/or feedbacks that need to be considered => chosen to focus on 4
- Disclosure: numerical modeler => primarily a data user as opposed to instrument developer

Roadmap

- SF1: Vertical Motion Feedbacks
- SF2: Hydrometeor Size Distributions
- SF3: Graupel and Hail Characteristics
- SF4: Vertical Location of Aerosols

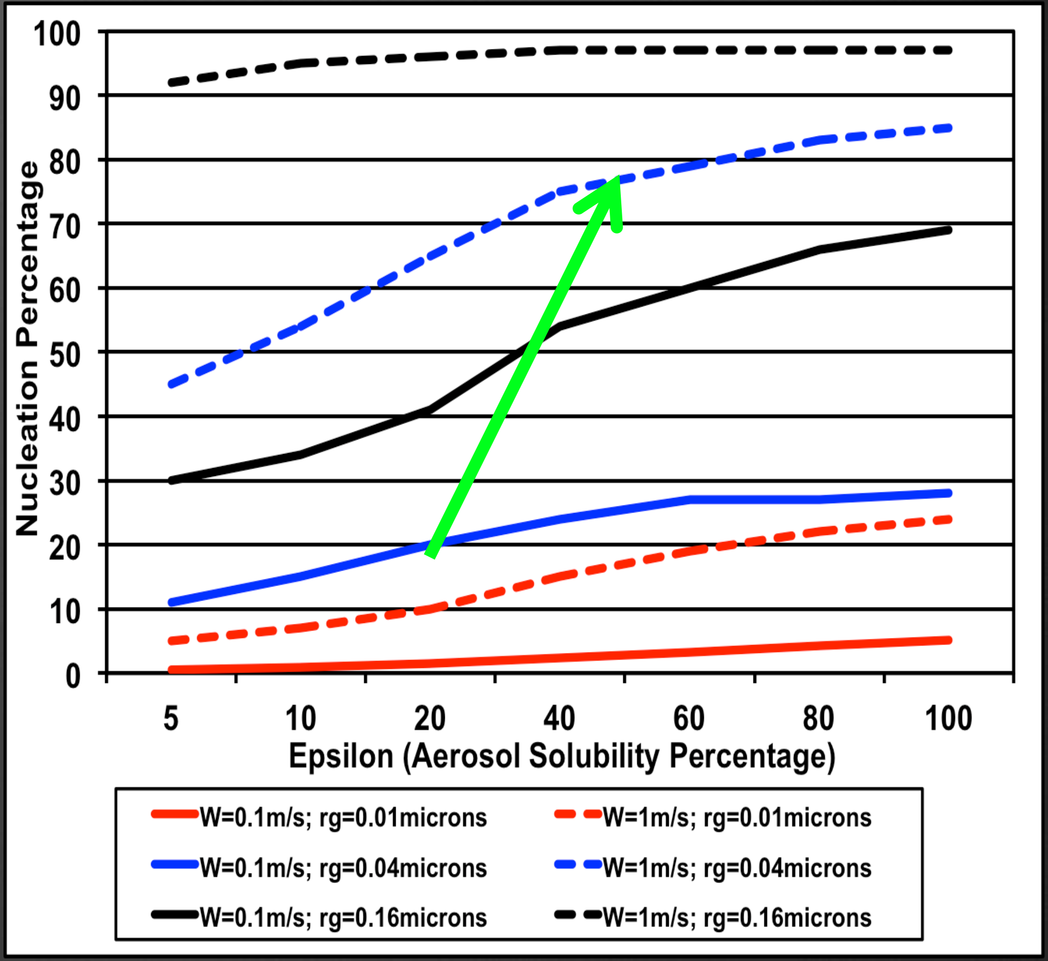
Science Frontier 1: Vertical Motion

Assess the Feedbacks between Vertical Motion and Aerosol, Microphysical and Cloud-Radiative Processes

W => Supersaturation and Aerosol Nucleation

- Supersaturation => explicit function of vertical velocity
- Supersaturation => aerosol nucleation and hydrometeor growth

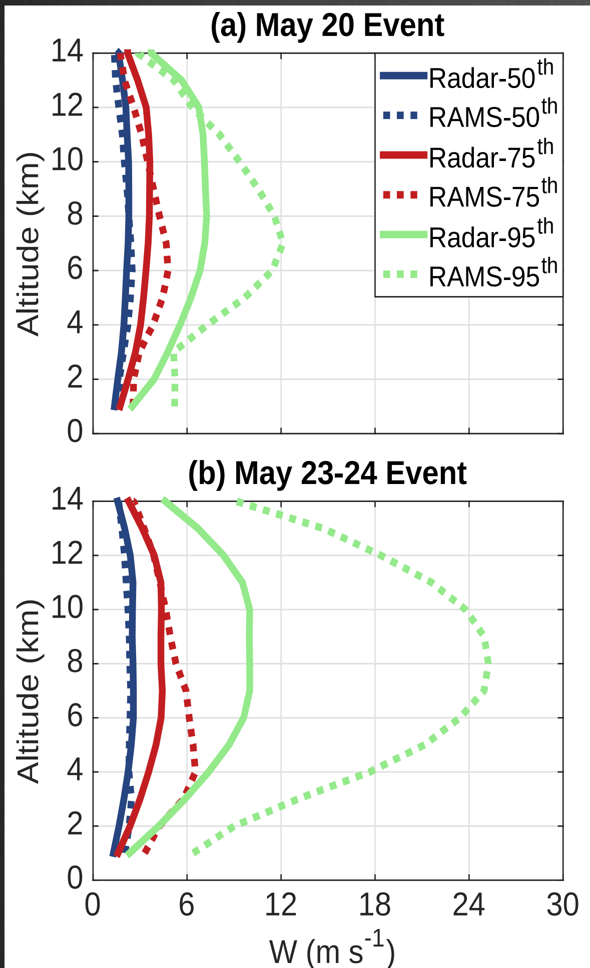
Increasing nucleation percentage with increasing vertical velocity



Percentage of nucleated cloud droplets as a function of W, median radius and solubility (after Saleeby and van den Heever 2013)

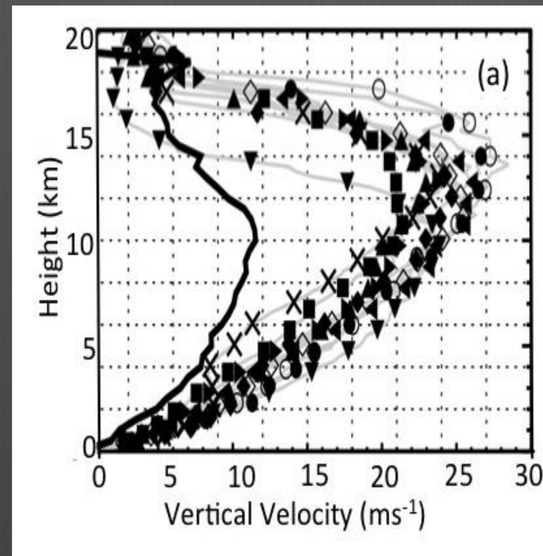
Simulated versus Observed Updrafts

Midlatitude squall lines (MC3E)



50th, 75th, and 95th percentiles of radar derived and simulated vertical velocities within convective updrafts for (a) May 20 and (b) May 23-24 MC3E squall lines (after Marinescu et al 2016)

Tropical convection (TWP-ICE)



CRMs (symbols) compared with radar observations (solid curve) (after Varble et al 2014).

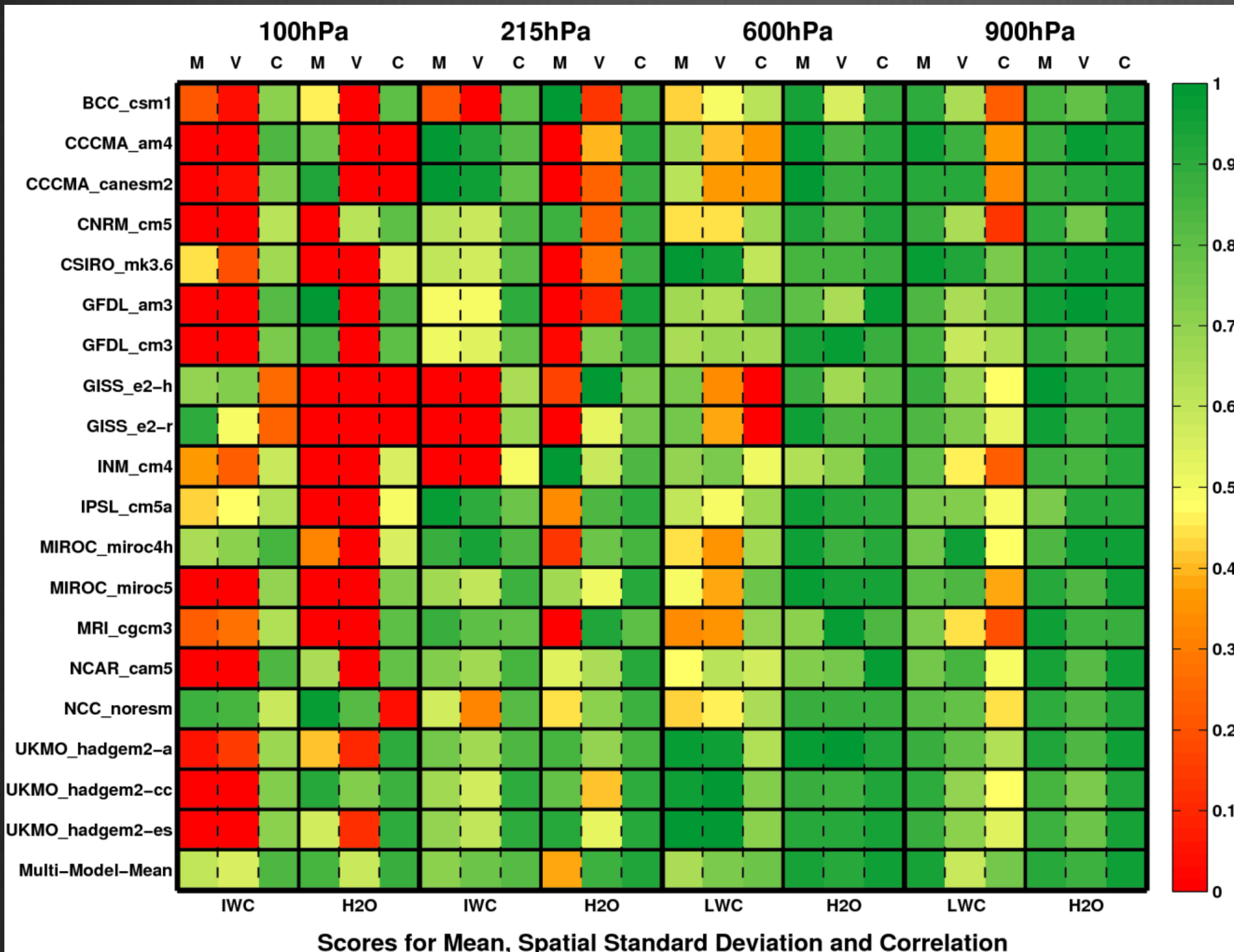
Fan et al 2015 found improvements with bin microphysics

CRMs overestimates of updraft velocities

=> attributed to assumptions made in microphysics parameterizations and microphysics-dynamics feedbacks

$$\frac{\partial w}{\partial t} = -\frac{\partial}{\partial x}uw - \frac{\partial}{\partial y}wv - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\bar{\rho}ww - C_p\bar{\theta}\frac{\partial \pi'}{\partial z} + g\left(\frac{\theta'}{\bar{\theta}} + 0.61q_v' - q_l\right) + D_w$$

W => Upper Tropospheric Water Vapor and Ice



Summary of CMIP5 performance

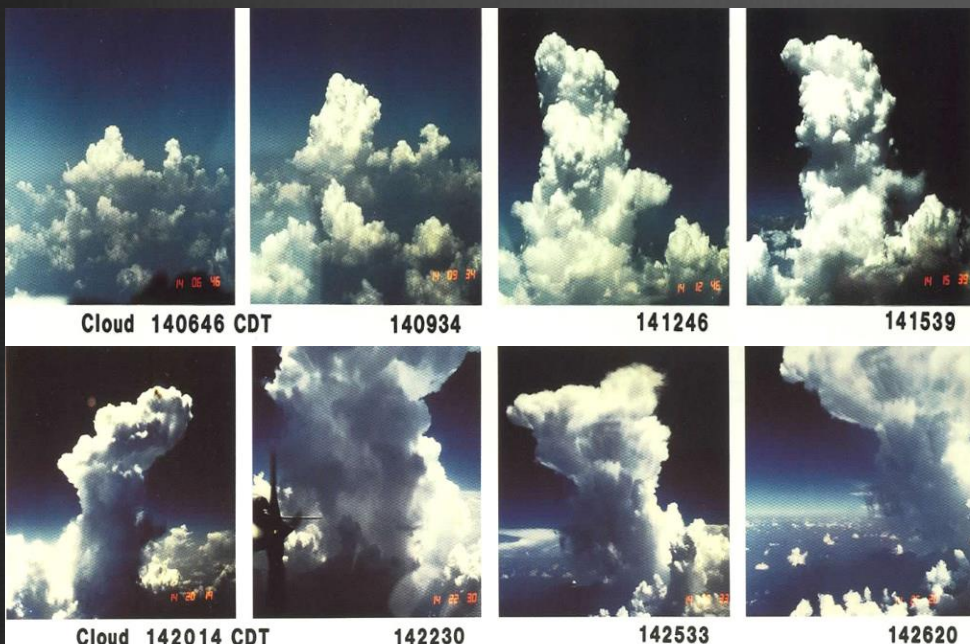
Shortfalls attributed in part to convective parameterization shortfalls

Impacts cloud-radiative forcing

(after Jiang et al. 2012)

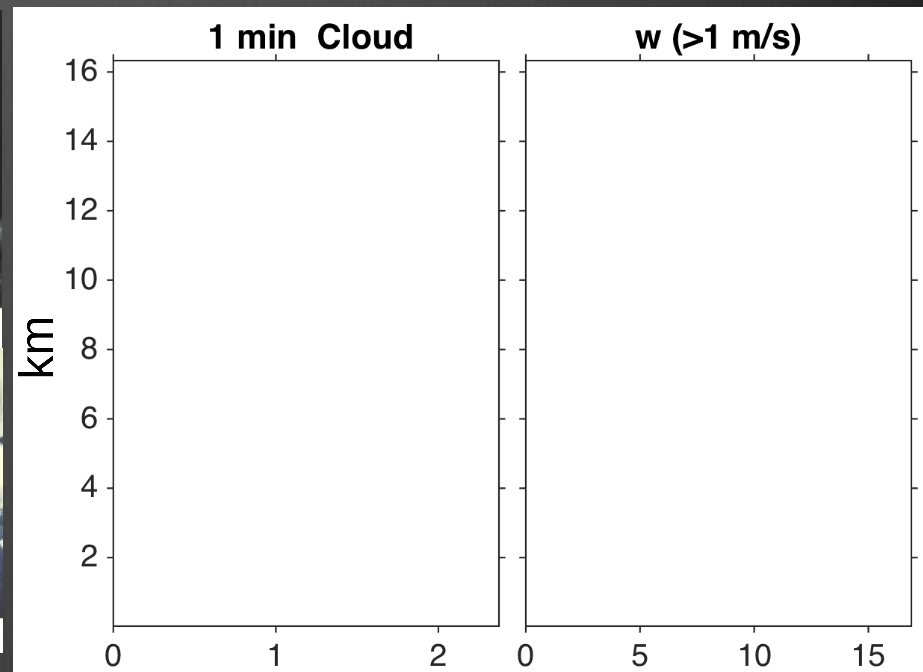
W => Rapid Cloud Evolution

Observations



Development of a deep convective cloud over 20 minute time period (Ted Fujita; provided by Tao)

Simulations

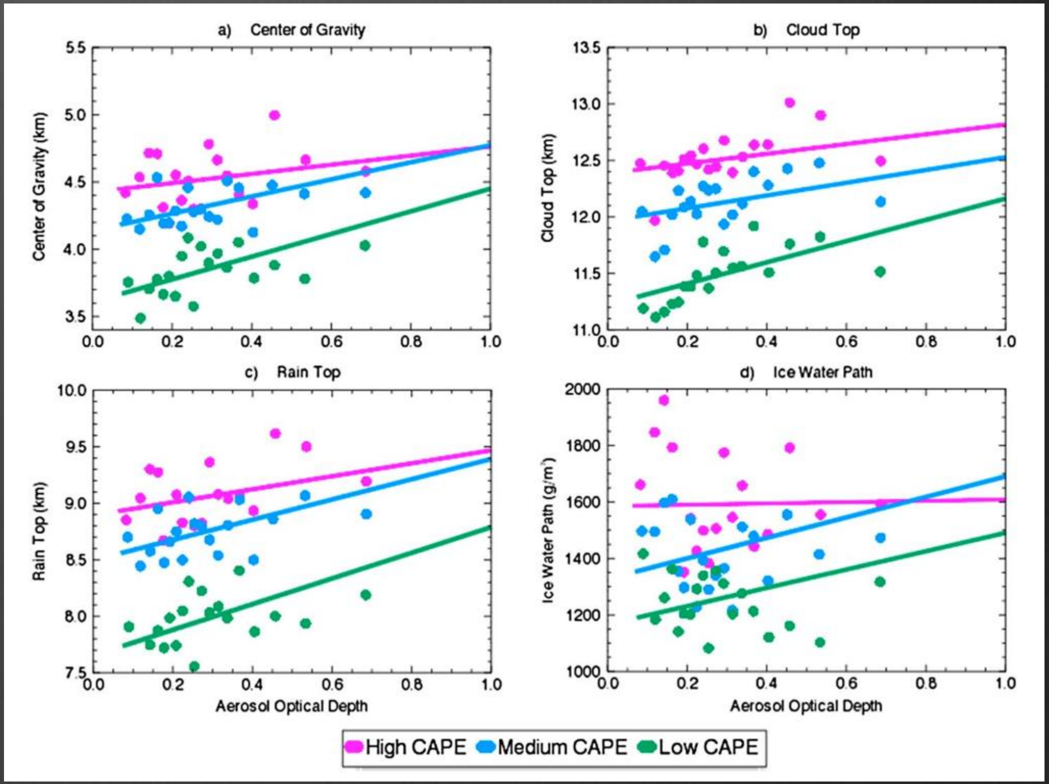


Profiles of cloud mixing ratios (g/kg) and vertical velocity (m/s) averaged over the updraft in a developing deep convective storm at 1 minute time intervals (figures Leah Grant)

Environmental Modulation of Convective Invigoration

Aerosol indirect effects modulated by:

- Relative humidity (Khain et al 2008)
- CAPE (Storer et al 2010, 2013)
- Shear (Fan et al 2009)



CloudSat average values of (a) center of gravity, (b) cloud top height, (c) rain top height and (d) IWP as a function of AOD and stratified by CAPE (after Storer et al 2013)

Observations - Wish List Dynamical Feedbacks

Observation Data Needs	Requirements	Comments	Platform
• Updraft / downdraft vertical velocity • Base state variables within the updrafts / downdrafts • Liquid water and ice mixing ratios and number concentrations	• Co-located • Global • High temporal frequency (mins) • Storm lifetime • Convective storm types • Range of environments	• Multi-frequency, dual-Doppler radar • In situ measurements	Space-borne Cubesats
• Supersaturation within convective updrafts			
• Microphysical process information		• Novel techniques to assess processes	

Science Frontier 2: Hydrometeor Size Distributions

Evaluate the Role of Hydrometeor Size Distributions in Microphysical Processes and Cloud-Radiative Forcing

Hydrometeor Size Distributions

- Limited understanding:
  - factors impacting hydrometeor size distributions
  - impacts of size distributions on microphysical and radiative processes
- Bulk microphysics parameterizations – need to make some a priori assumption about the size distribution
- Bin microphysics parameterizations prognose temporal and spatial evolution of size distribution

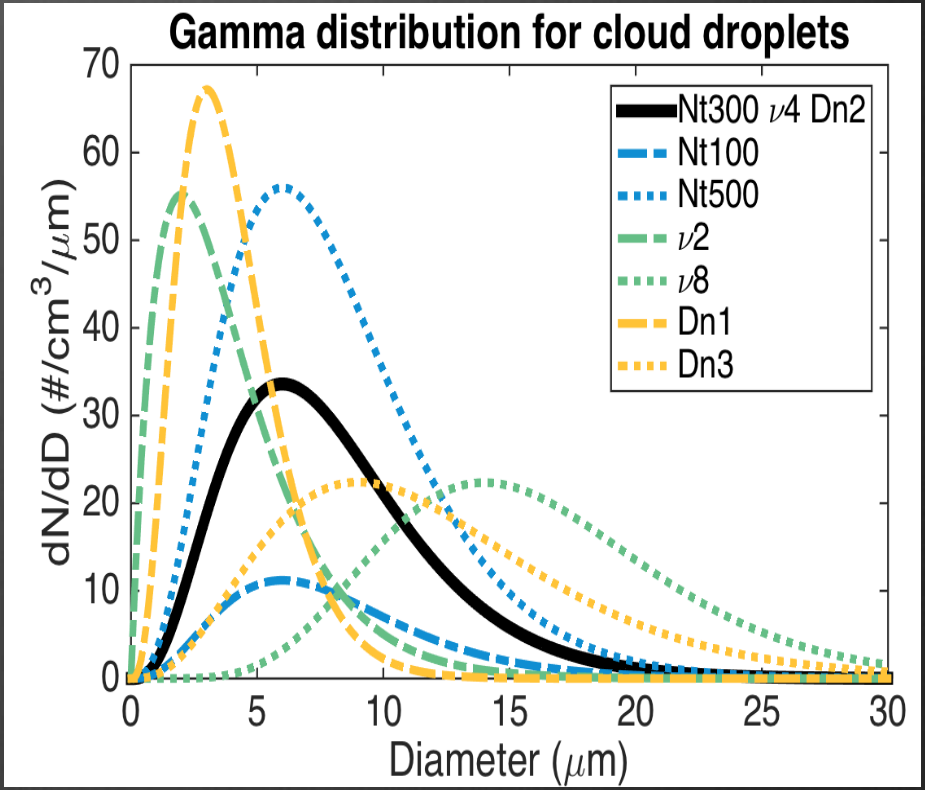
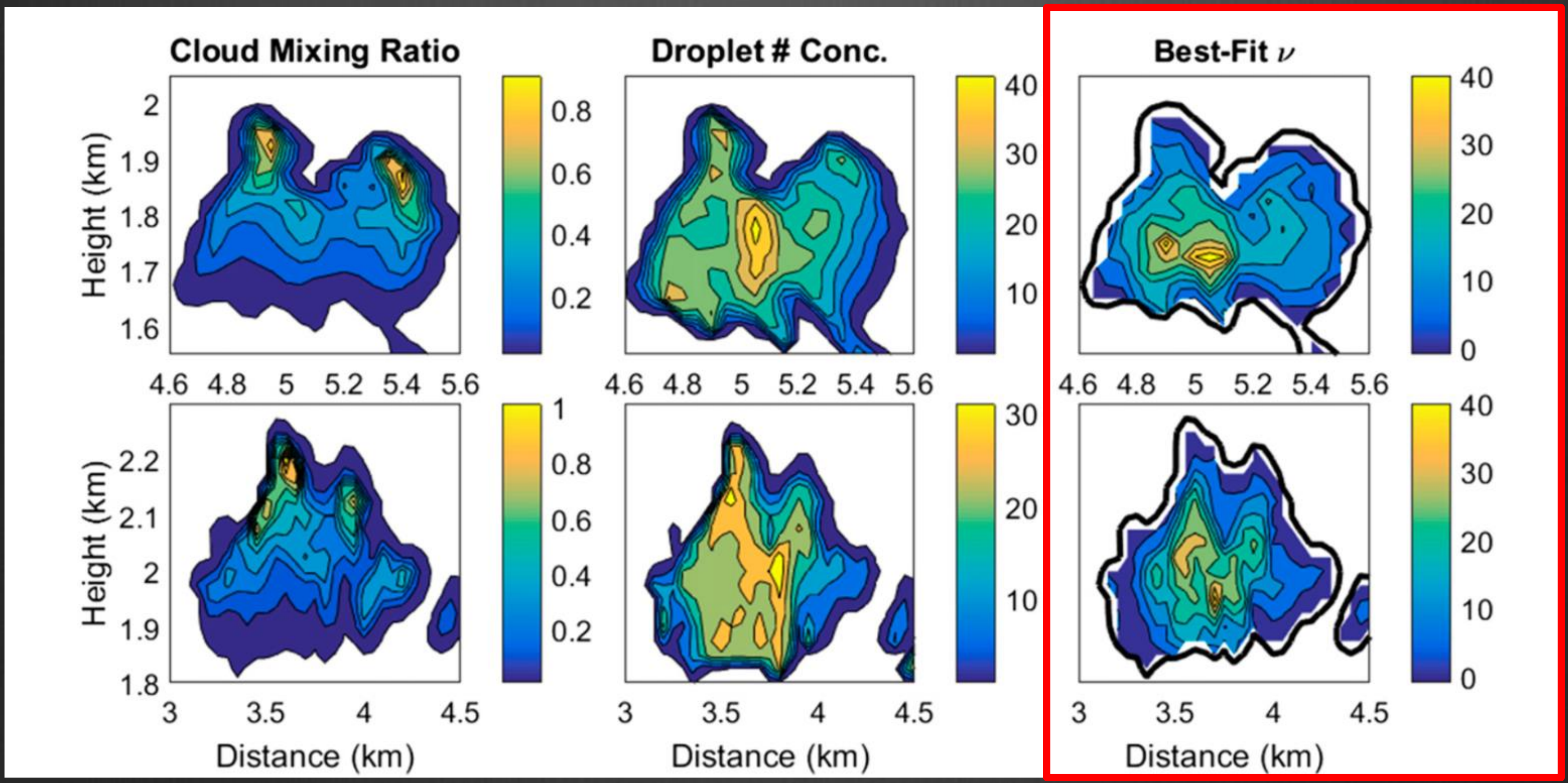


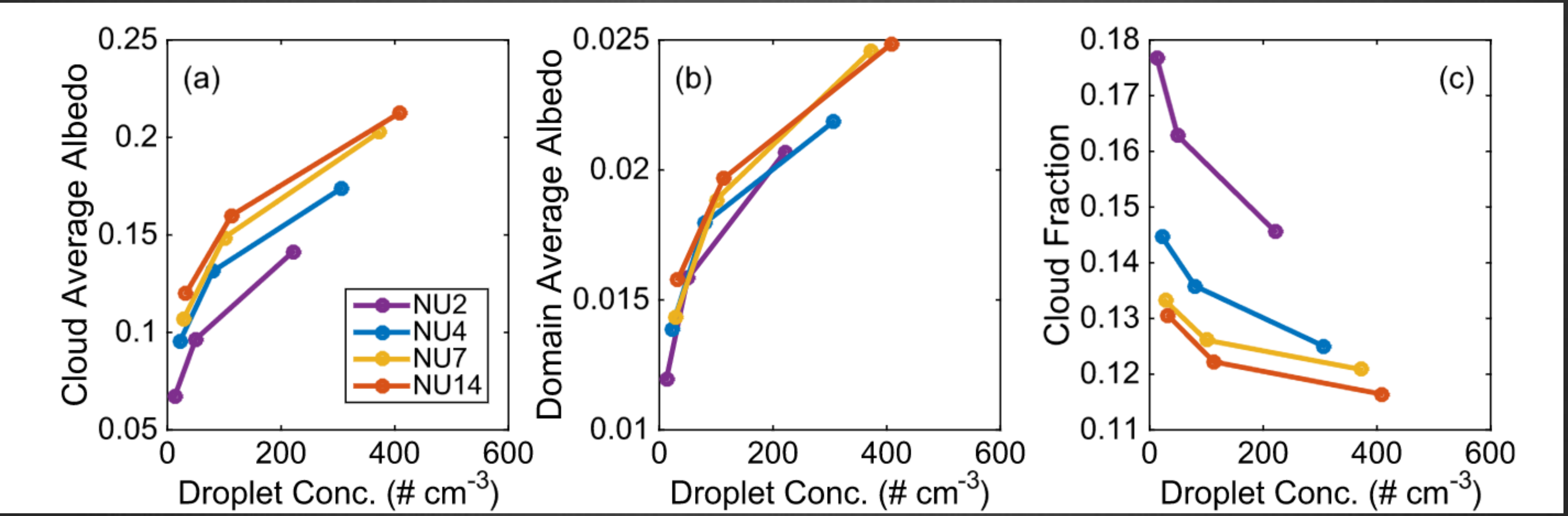
Figure demonstrating the impacts of various parameter assumptions on cloud droplet size distributions

Best-Fit Shape Parameters from Bin Simulations of Cumulus Clouds



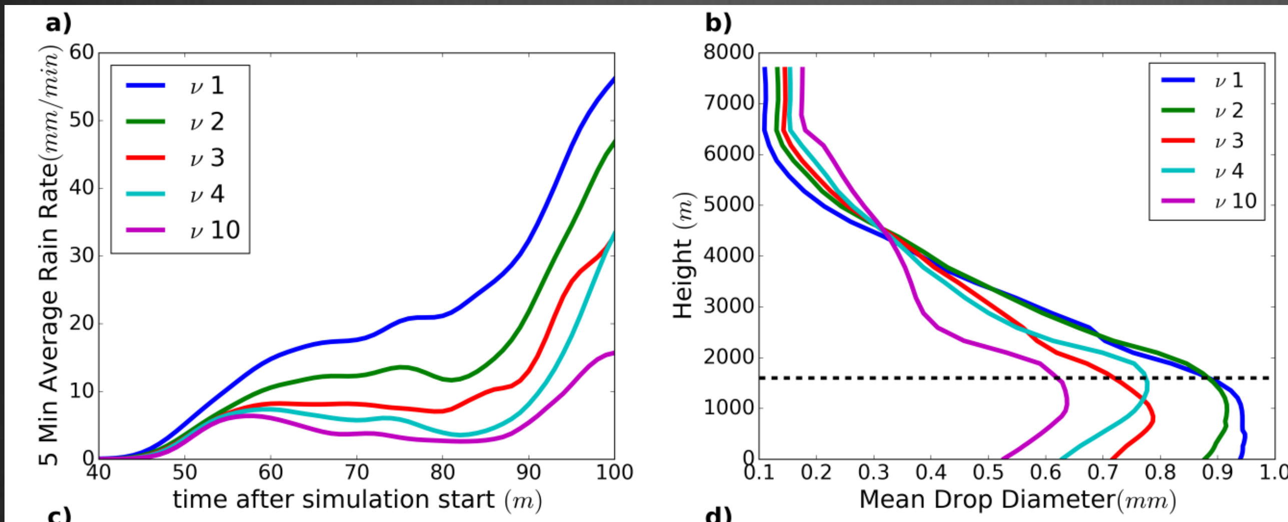
Cross sections of two different cumulus clouds simulated using the spectral bin microphysics (after Igel and van den Heever 2017)

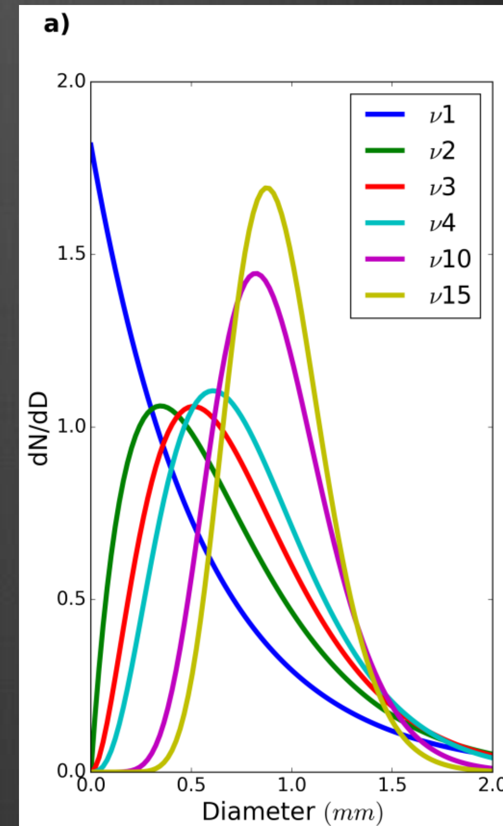
Shape Parameter, Aerosols and Cloud-Radiative Forcing

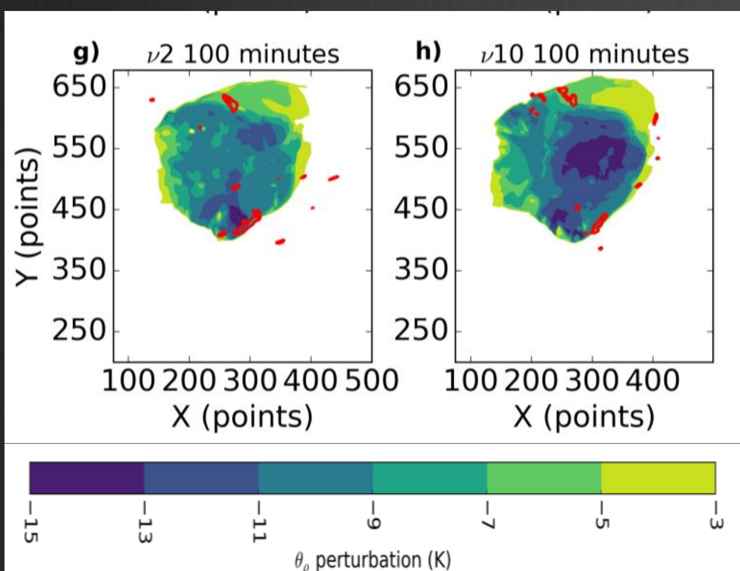


(a) Cloud-average albedo, (b) domain-average albedo and (c) cloud fraction as a function of droplet number concentration for various shape parameter settings in BULK simulations. Points from left to right represent increasing aerosol concentrations (after Igel and van den Heever 2017b)

Impacts of Rain Shape Parameter







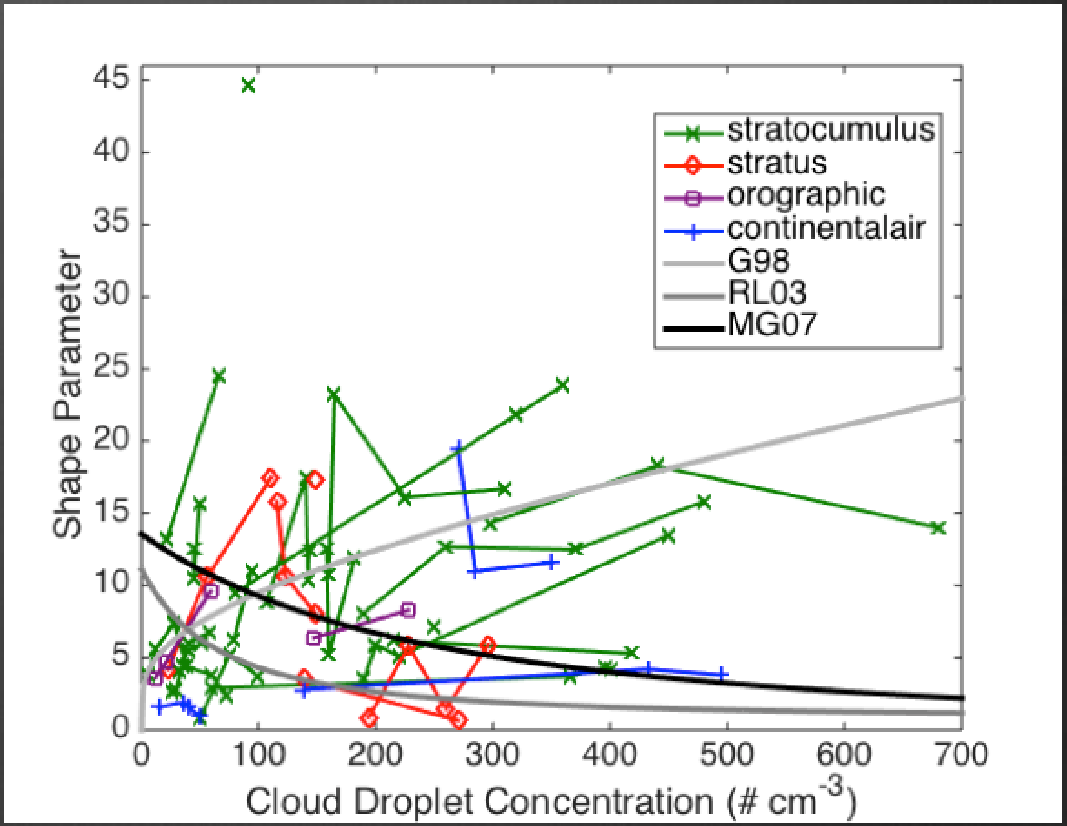
Temperature perturbations on the order of 5-6 K for shape parameter range tested here ….

Shape parameters arbitrarily chosen

(after Freeman, Igel and van den Heever 2017)

Observations of Cloud Droplet Shape Parameters

- Shape parameter observations necessary to evaluate BOTH bin and bulk approaches and to guide parameter settings in BULK schemes
- Ultimately necessary to understand cloud processes



Shape parameter values as a function of cloud droplet concentration as reported by Miles et al. (2000) using 16 previous studies. Gray and black lines show previously proposed relationships (Graboski 1998; Rotstayn and Liu 2003; Morrison and Grabowski 2007) (after Igel and van den Heever 2017)

Observations - Wish List
Hydrometeor Size Distributions

Observation Data Needs	Requirements	Comments	Platform
• Liquid and ice hydrometeor number concentrations • Liquid and ice mixing ratios • Liquid and ice hydrometeor sizes	• Storm lifetime • Wide range of convective storm types • Wide range of environments	• In situ measurements	• UAVs / drones • Tethered balloons • Storm penetrating aircraft

Science Frontier 3:
Graupel and Hail Characteristics

Determine how the Characteristics of Graupel and Hail vary as a Function of Storm Morphology, Lifetime and Environment

Ice Processes

- Ice processes are arguably the largest roadblock to improving convective storm predictions:
  - Ice nuclei
  - Wide variety of ice species
  - Multiple process pathways
  - Lack of theoretical knowledge
- Graupel and Hail:
  - CRMs struggle to produce large graupel and /or hail at the surface
  - Many current bulk schemes require the choice between graupel and hail
  - Melting and riming have important thermodynamic and lightning implications but are poorly represented (e.g., Morrison and Grabowski 2010; Saleeby and Cotton 2008)

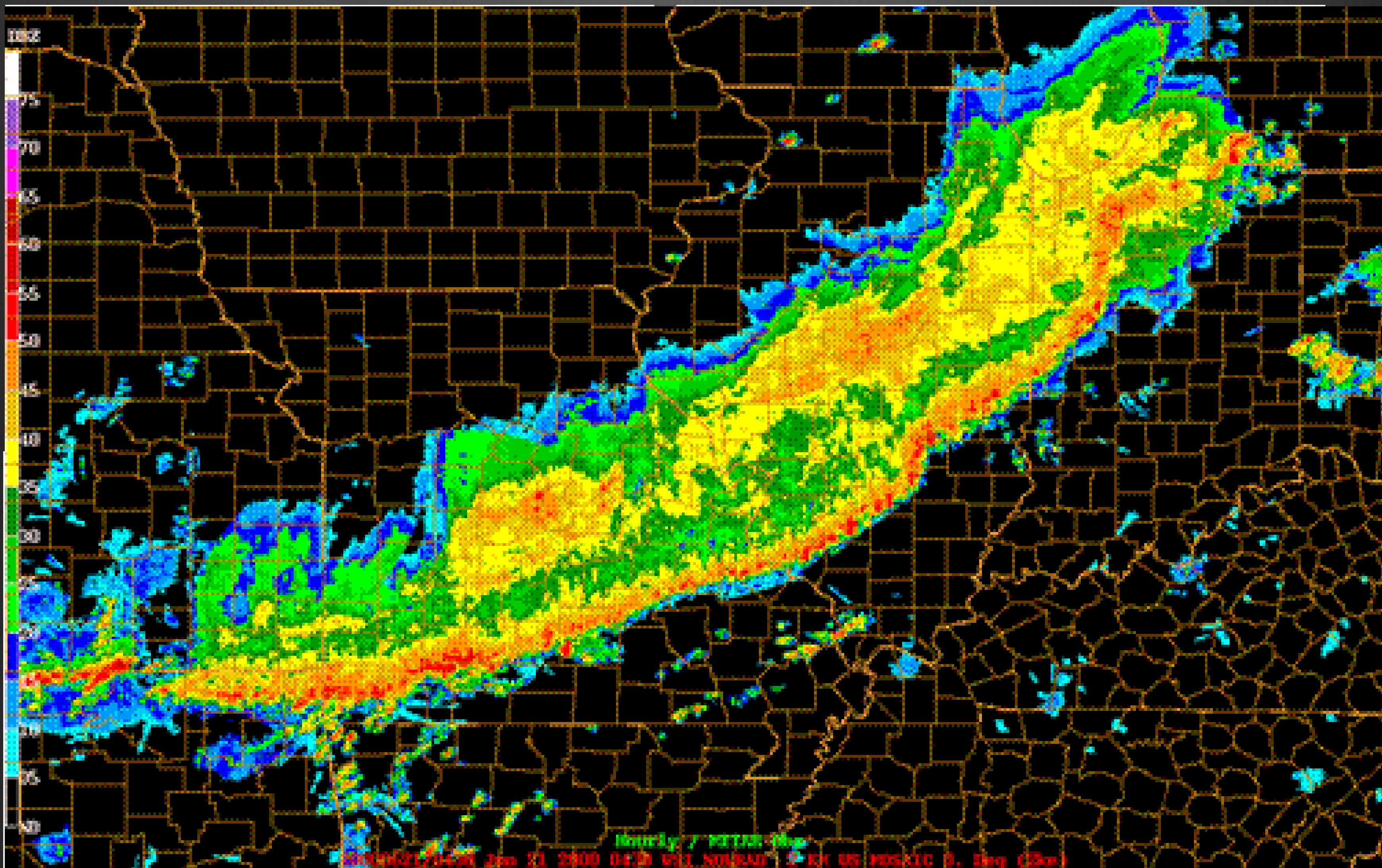
Graupel versus Hail Experiments

Graupel-like

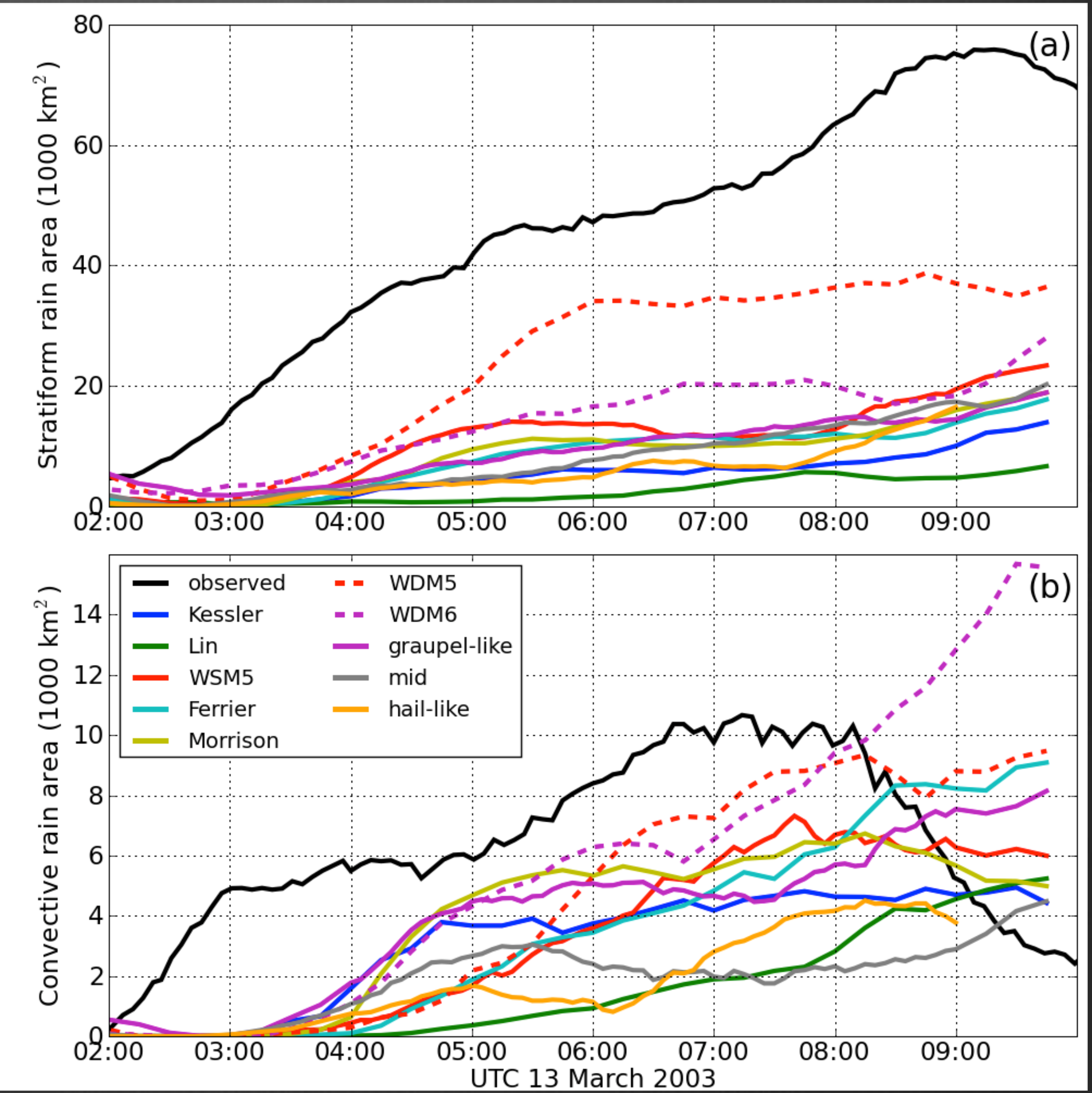
Hail-like

0600 UTC

0800 UTC



- Stratiform area varied over 200%
- Convective area by as much as 300%
- Simply due to choice of graupel or hail scheme



(after Adams-Selin et al 2013)

Observations - Wish List
Hail and Graupel

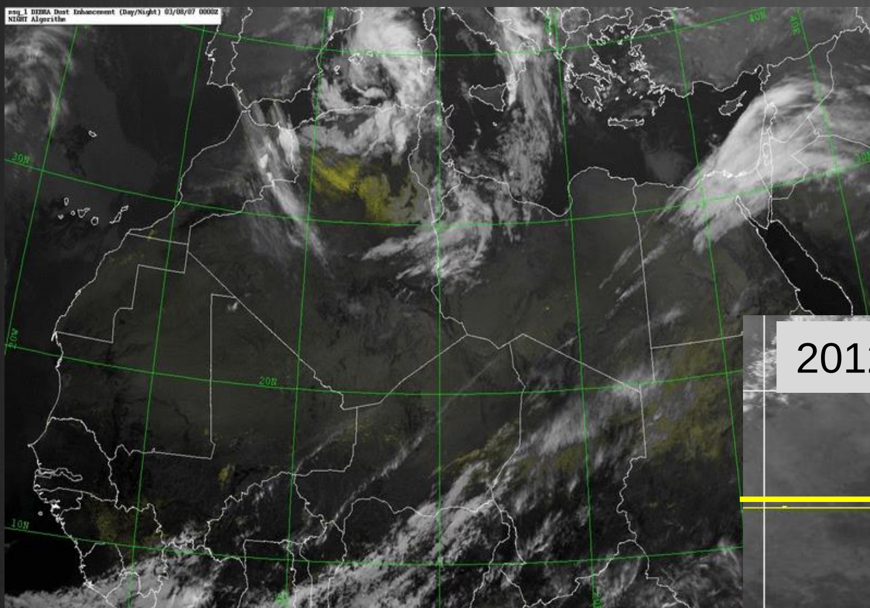
Observation Data Needs	Requirements	Comments	Platform
• Hail and graupel number concentrations at the surface and within storm • Hail and graupel sizes at the surface and within storm • Hail and graupel mixing ratios within storm • Hail and graupel density (P3 scheme)	• Over storm lifetimes • Wide range of convective storm types • Wide range of environments	• In situ measurements • Additional field campaigns focused on graupel and hail	• Storm penetratin g aircraft
• Role of formation processes		• Novel techniques to assess processes	

Science Frontier 4:
Vertical Aerosol Profiles

Analyze the Impacts of the Vertical Location of Aerosols on Cloud Microphysical and Radiative Processes

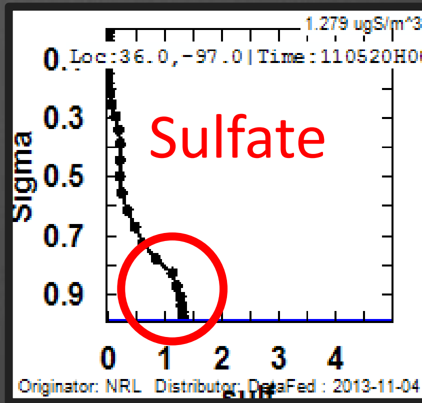
Vertical and Horizontal Transport

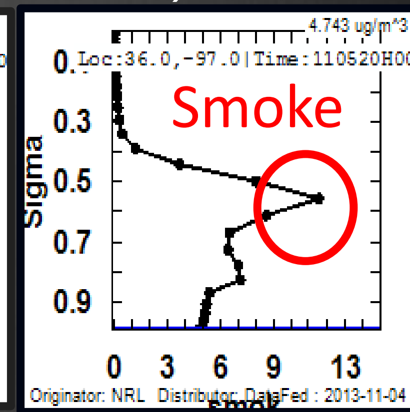
Aerosols are lofted and transported on synoptic through mesoscale

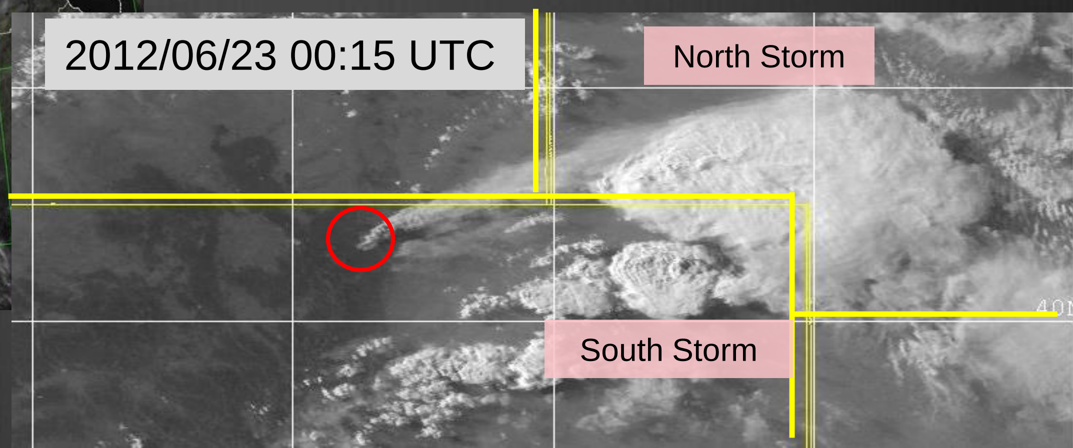


Images provided by Steve Miller (CIRA)

Aerosol Profiles impacting MC3E MCS (plots from Sonia Kreidenweis; more recently Fridland et al 2017)



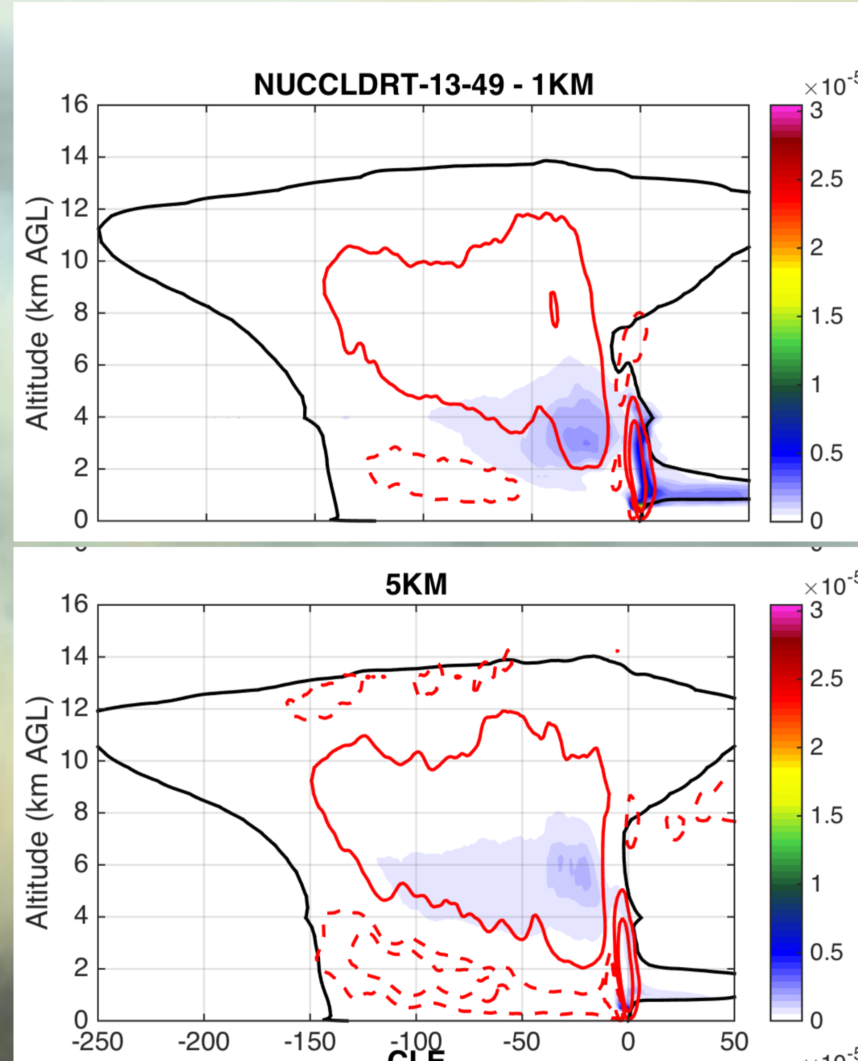




DC3 case studies (Barth et al 2015) Annotated satellite photo from Apel et al. (2015)

Vertical Distribution of Aerosols

- Impacts convective instability (Grant and van den Heever 2014; Saide et al 2015; Fan et al 2015)
- Influences amount of aerosol ingested (Lebo 2014; Marinescu et al 2017)
- Secondary nucleation
- Large uncertainties regarding the amount of aerosol that is ingested into updrafts (Seigel and van den Heever 2012)



Cloud water nucleation rates occurring in association with low-level and elevated aerosol layers (Marinescu et al 2017)

Yucatan Peninsula Biomass Burning: http://www.firelab.org/project/biomass-burning-mexico

Observations - Wish List
Vertical Distribution of Aerosols

Observation Data Needs	Requirements	Comments	Platform
• Profiles of cloud nucleating and ice forming AP number concentrations, mass and size • Profiles of cloud nucleating and ice forming AP composition	• NEAR and WITHIN storm environments • Over storm lifetimes • Wide range of environments	• In-situ measurements	• UAVs / drones • Tethered balloons • Storm penetrating aircraft

Summary

- SF1: Assess the Feedbacks between Vertical Motion and Aerosol, Microphysical and Cloud-Radiative Processes
- SF2: Evaluate the Role of Hydrometeor Size Distributions in Microphysical Processes and Cloud-Radiative Forcing
- SF3: Determine how the Characteristics of Graupel and Hail vary as a Function of Storm Morphology, Lifetime and Environment
- SF4: Analyze the Impacts of the Vertical Location of Aerosols on Cloud Microphysical and Radiative Processes