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Integrated Cloud, Land-Surface,& Aerosol System Study ICLASS

A Critical Evaluation of the Evidence for Aerosol Invigoration of Deep Convection

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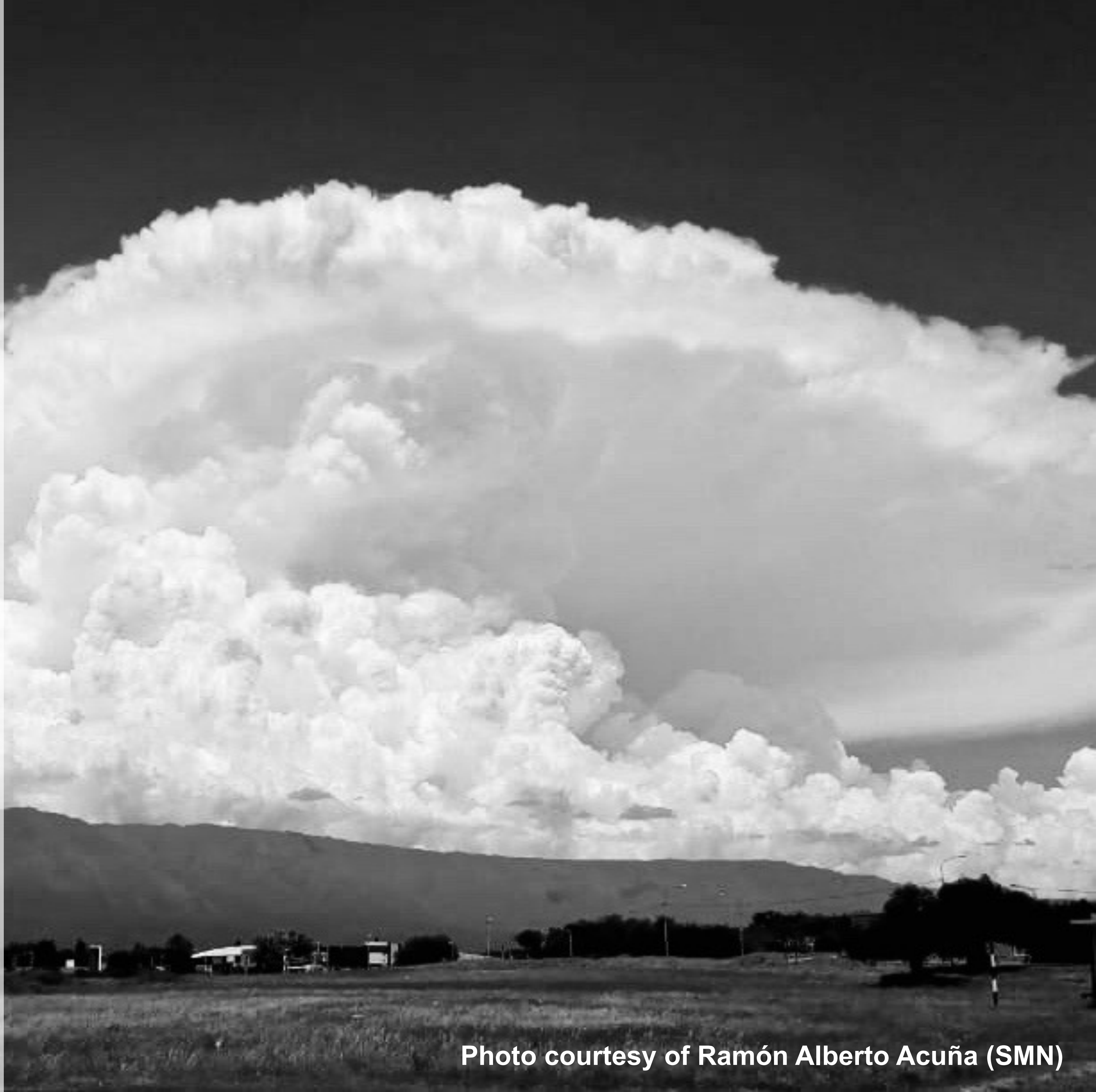

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Opinion: A Critical Evaluation of the Evidence for Aerosol Invigoration of Deep Convection

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Special Issue: 20 Years of *Atmospheric Chemistry and Physics*

We review theoretical, modeling, and observational foundations for aerosol invigoration of deep convective updrafts focused on:

- (1) mixed/cold/fusion invigoration whereby higher CCN increases drop concentration, suppressing warm rain production, leading to greater lofting of liquid condensate that increases fusion heating when it freezes, and
- (2) warm/condensation invigoration whereby higher CCN and drop concentration reduces supersaturation to increase condensation.

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Theoretical Foundation

Flood or Drought: How Do Aerosols Affect Precipitation?

DANIEL ROSENFELD, ULRIKE LOHMANN, GRACIELA B. RAGA, COLIN D. O'DOWD, MARKKU KULMALA, SANDRO FUZZI, ANNI REISSELL, AND MEINRAT O. ANDREAE Authors Info & Affiliations

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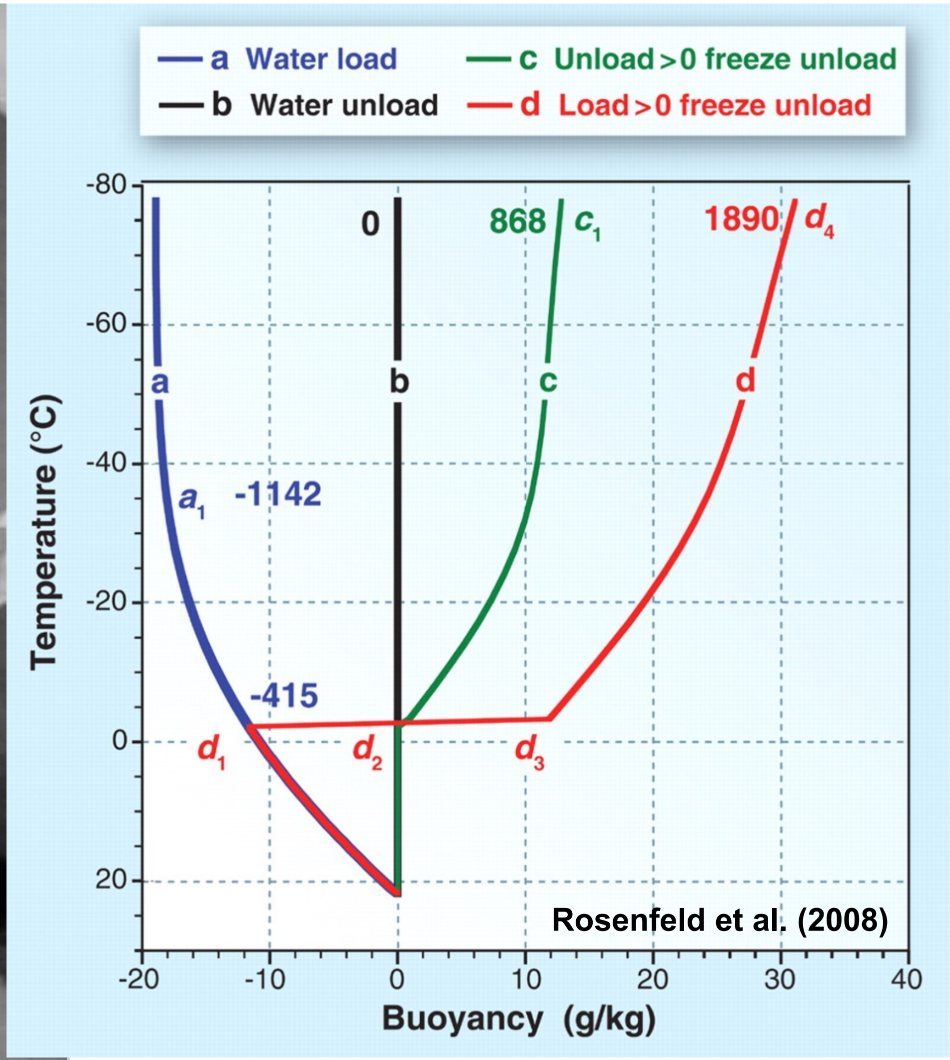
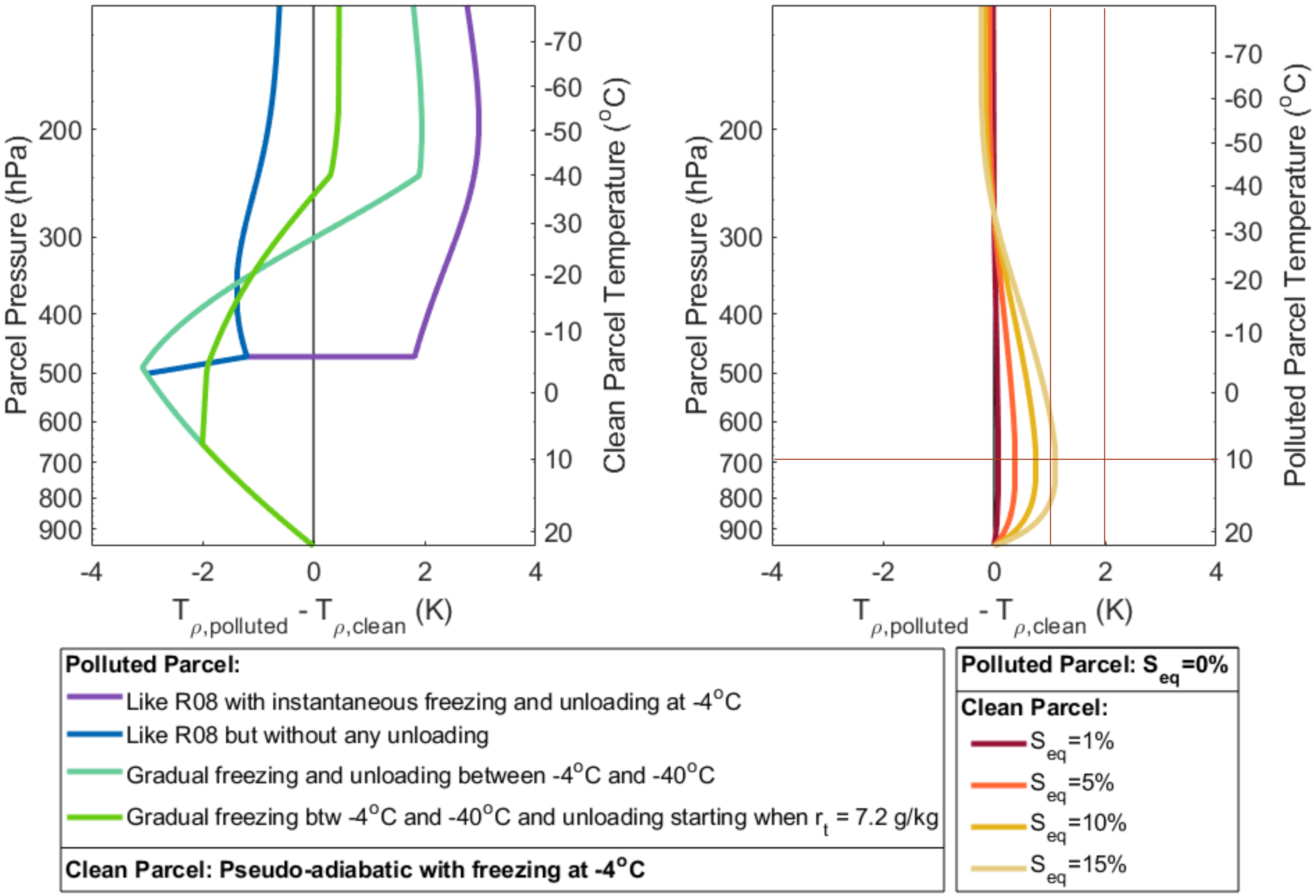


- The cold phase (fusion) pathway critically relies on liquid freezing very quickly and unloading upon freezing.
- Relaxing these assumptions shows that effects could be weakly positive or negative depending on the situation.
- Warm phase (condensational) invigoration depends on updrafts reaching large supersaturations that do not yet have observational backing.

Following Igel and van den Heever (2021, GRL)



Modeling Recommendations

To improve model-derived sensitivities of deep convective clouds to aerosols:

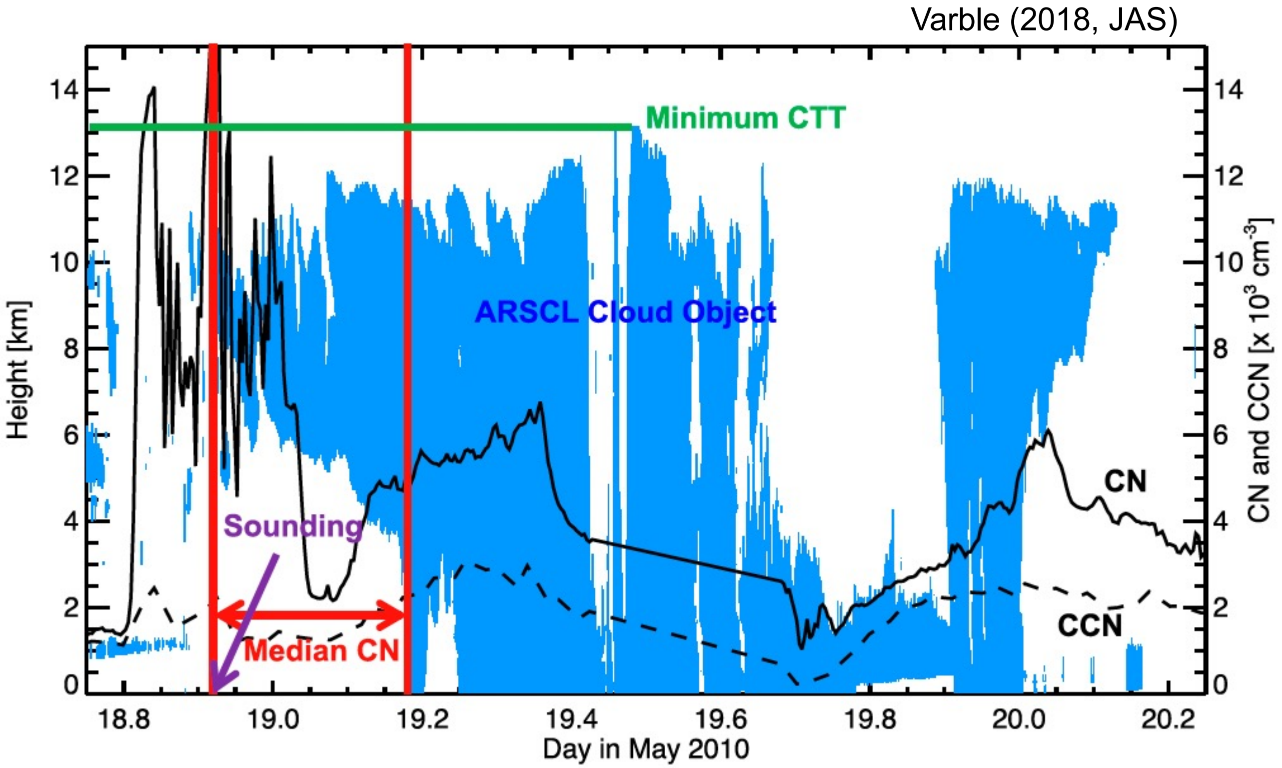
1. Continue improving the representation of updraft dynamics and microphysics.
2. Expand usage of LES to limit resolution-related biases.
3. Avoid strong conclusions based on a single simulation; assess robustness with initial/boundary condition ensembles, simulations across different convective regimes, and model intercomparisons.
4. Consider limitations of boundary conditions, time integration, domain size, and physics parameterizations in application to the real world.
5. Use objective and representative sampling of model output.
6. Provide observational context to assess confidence in model-derived sensitivities.

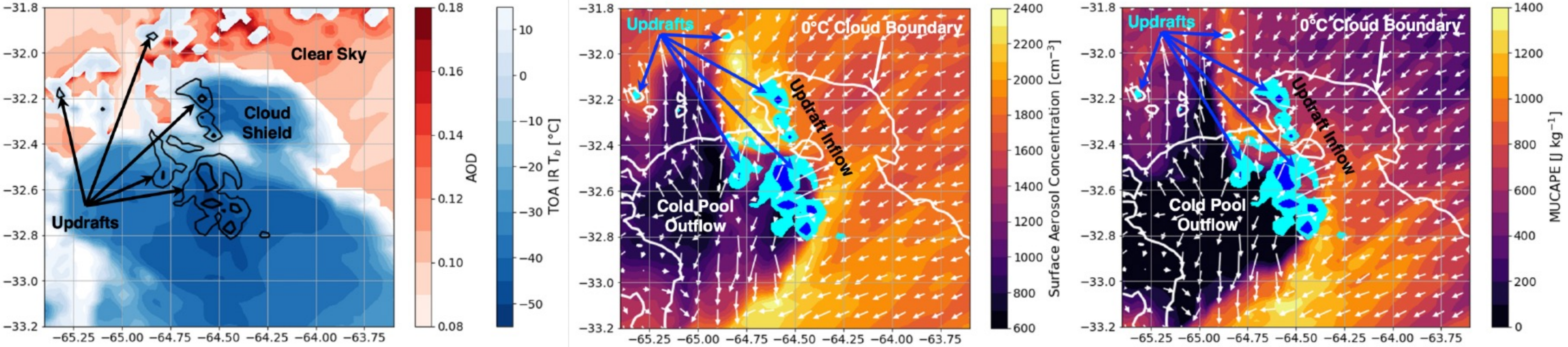
It is usually not possible to do all the above in any single study, but shortcomings with respect to any of the above can cause misleading results and incorrect interpretations. Because of that, consensus across a multitude of studies using differing approaches and datasets is vitally important, as is clearly understanding (and explaining) of methodologies, uncertainties, and caveats.

Observational Recommendations

To improve observational studies assessing aerosol effects on deep convection:

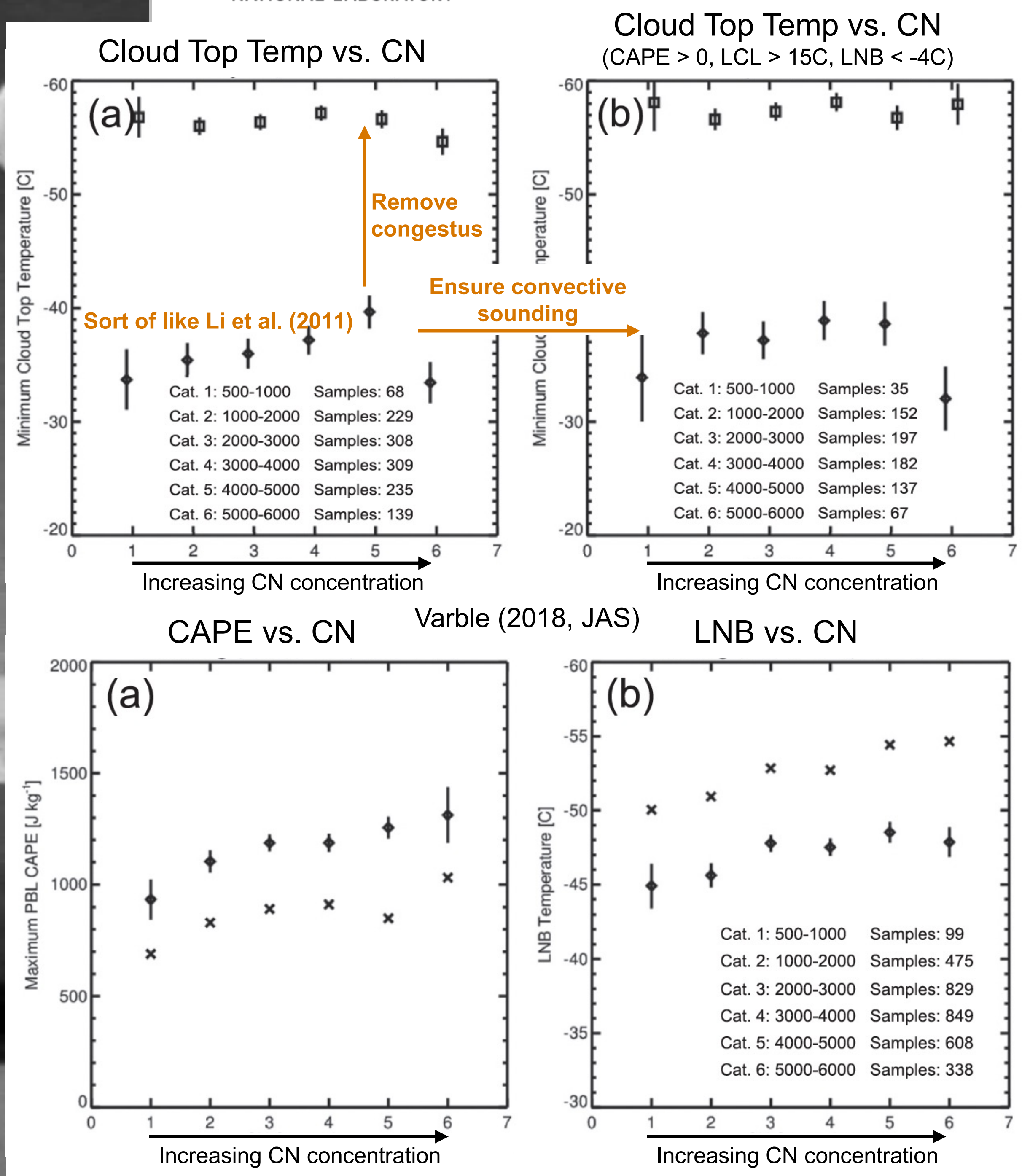
1. Continue improving CCN, convective updraft, and atmospheric state retrievals; consider impacts from deficiencies of proxies used in analyses.
2. Isolate single convective cloud types (e.g., purely liquid vs. mixed phase) and assess the representativeness of sampling times and locations.
3. Avoid post-hoc or subjective selections of sampling times and regions that fit a preconceived narrative.





Model output example of major variability in the values of key variables depending on where (and when) measurements are obtained.

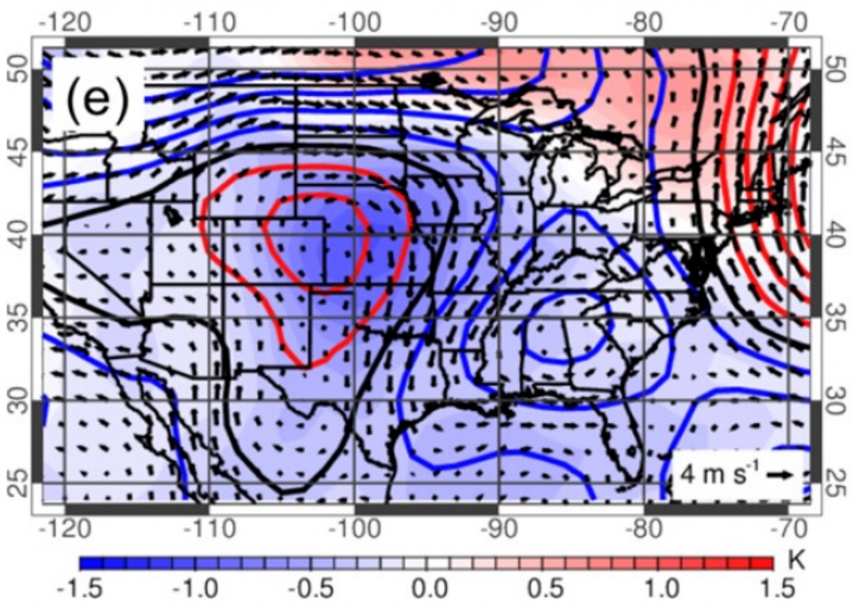
Observational Recommendations (Continued)



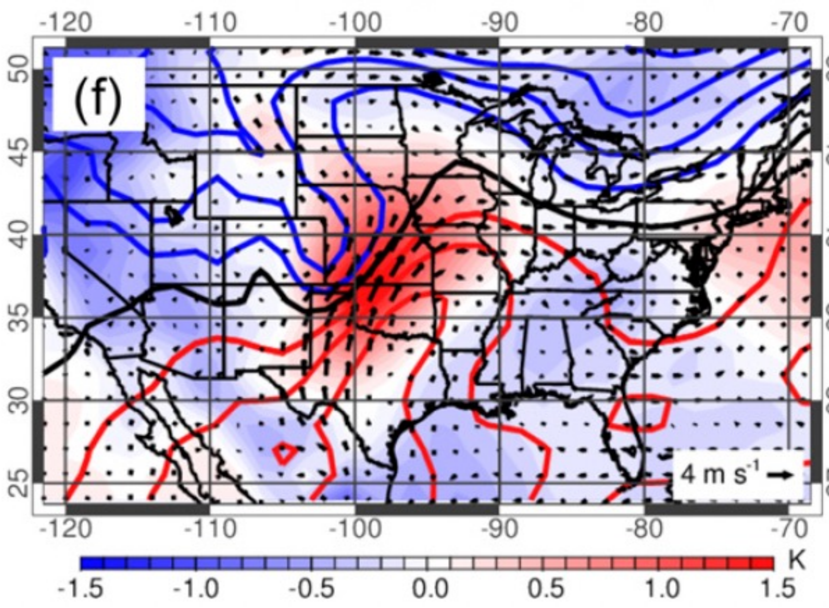
4. Control for atmospheric parameters known to modulate convection (e.g., LNB for cloud top height) by performing multivariate analyses that account for covariabilities between *all* predictor variables.
5. Apply appropriate significance testing accounting for dependent sampling and non-parametric distributions.
6. Avoid adopting explanations from previous studies without evidence that such explanations are more likely than alternatives.

Unlike modeling recommendations, much of the above is achievable in individual studies.

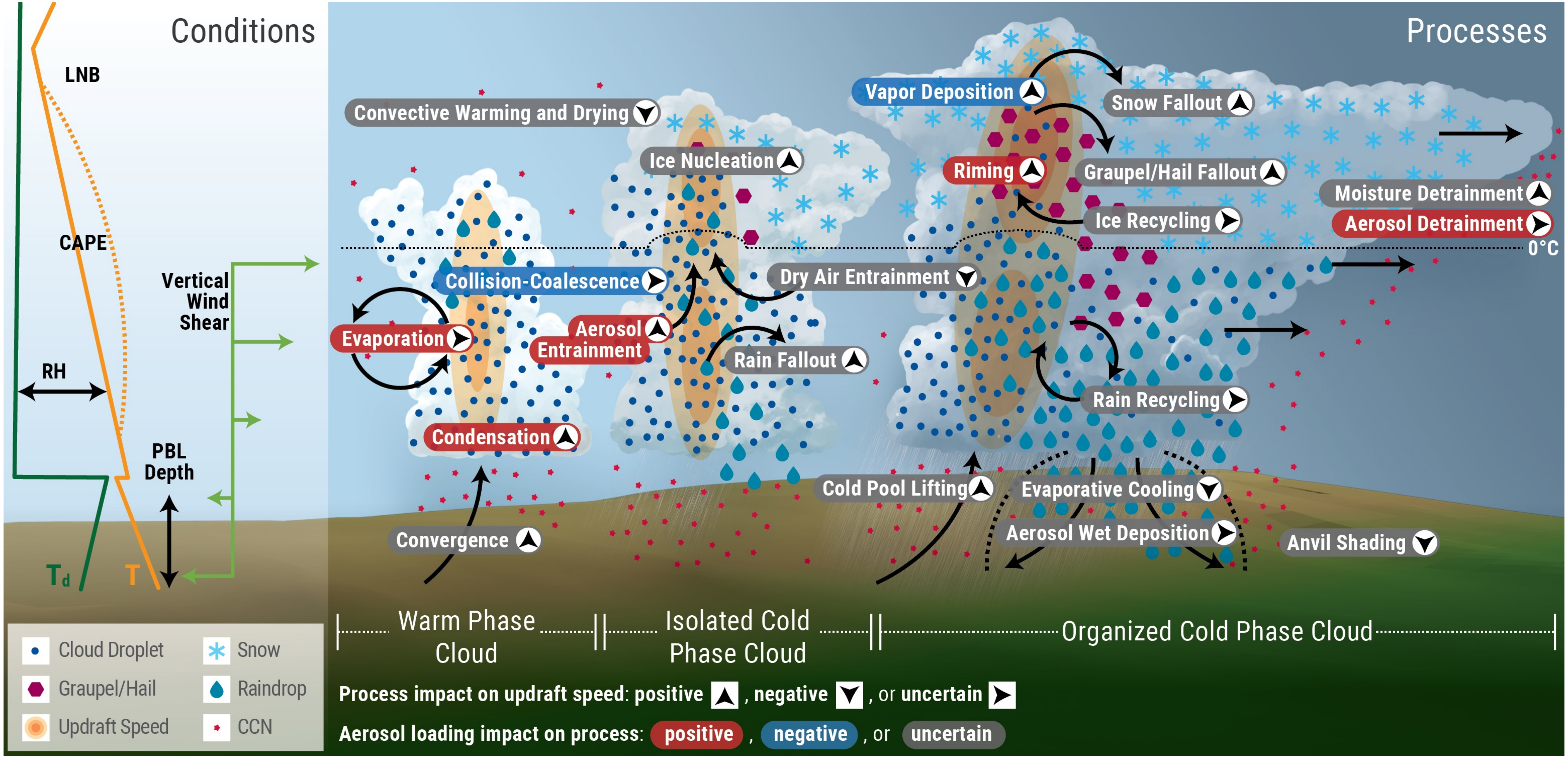
200-hPa Temp and Height (High-Low Aerosols)



850-hPa Temp and Height (High-Low Aerosols)



Many conditions and processes modulate aerosol-deep convection relationships that are highly variable and not well quantified



A Path Forward?

1. Agree on a definition for deep convection invigoration, e.g., an increase in updraft speed, and that this cannot be necessarily inferred from microphysical changes alone.
2. Estimate expected magnitudes of aerosol effects across a variety of atmospheric and cloud conditions so that observational and modeling approaches can be designed with sufficient accuracy, representativeness, and sample size to isolate such effects.
3. Expand supersaturation retrievals and evaluate their validity across a variety of updraft and cloud conditions.
4. Better quantify condensate loading, freezing depths, and buoyancy in observed updrafts.
5. Explore novel ways to infer real world updraft and CCN properties.
6. Is aerosol invigoration of convection receiving an outsized focus relative to other potentially impactful convective cloud processes with large uncertainties?